DESIGN AND CONSTRUCTION OF A LIQUID XENON TEST APPARATUS

BY

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THESIS

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ABSTRACT

This thesis discusses the design and initial construction of a liquid xenon test apparatus for the Enriched Xenon Observatory (EXO) experiment. The EXO collaboration aims to explore neutrinoless double beta decay using isotopically enriched Xe-136. It has already published several high impact physics result with EXO-200, and is in R&D stage for nEXO, a tonne scale experiment. The test apparatus is built for Next R&D studies, such as Xe purity, and electronics in liquid xenon. This thesis mainly talks about the system and mechanical design of the apparatus. Xenon system consists of several sub-systems, including experimental chamber, recirculation and purification loop, feed and bleed system, emergency recovery loop, auxiliary cooling sub-system, and slow control system. Several main tasks have already been completed, including mechanical design of different equipment, slow control system setup, database setup, thermodynamics calculation, and sensor testing and calibration. Finally, the thesis discusses commissioning and test plan for the apparatus.

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CHAPTER 1： INTRODUCTION

1.1. Enriched Xenon Observatory (EXO)

Enriched Xenon Observatory (EXO) is an experiment in particle physics aiming to detect “neutrino-less double beta decay” using large amounts of xenon isotopically enriched in the isotope 136 [1, 19]. The experiment currently consists of two facets:

- EXO-200, a 200-kilogram prototype experiment currently operating at Waste Isolation Pilot Plant (WIPP). It has measured for the first time the two-neutrino mode of double beta decay of xenon 136. It has also set the most stringent limit on the rate of neutrinoless double beta decay.
- nEXO, (“next EXO”), a tonne scale experiment using Xenon 136 to search for neutrinoless double beta decay. The collaboration is undergoing extensive R&D to design the xenon detector and a way to “tag” the barium daughter ion produced by the decay in order to eliminate all backgrounds.

As to EXO-200, 200 kg of liquid xenon enriched to 80% of 136 isotope is filled in the Time Project Chamber (TPC) vessel. When a particle deposits energy in liquid xenon, it ionizes the xenon atoms, knocking electrons off. If electric field is applied to xenon, the electrons will be pushed to the wire grids. The grid position provide a 2D location, and the number of electrons is related to the event’s energy.Some xenon ions recombine with electrons, making xenon atoms into excited states. When excited atoms relax, they release ultraviolet light, known as scintillation, which is collected on avalanche photodiodes. The amount of light is related to the event’s energy. Combining the ionization and light signals allows a better energy measurement than using either signal on its own.

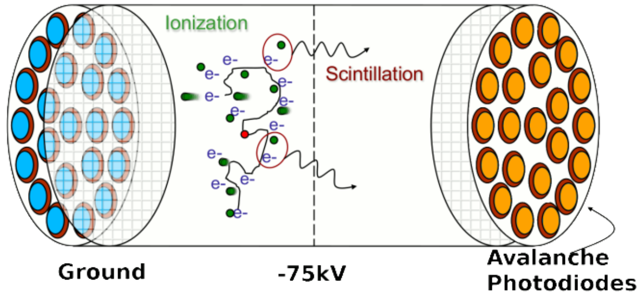

Fig 1.1: Electric Field to Collect Electrons to Wire Grids

Fig 1.2 shows the cryostat system for EXO-200. TPC vessel is assembled within the cryostat system to keep xenon as liquid phase. The vessel is contained in a volume of HFE-7000, a synthetic fluid, and the HFE is in a large copper cryostat, with vacuum gap for insulation. The system is shielded with lead from radioactive from backgrounds and cosmic rays.

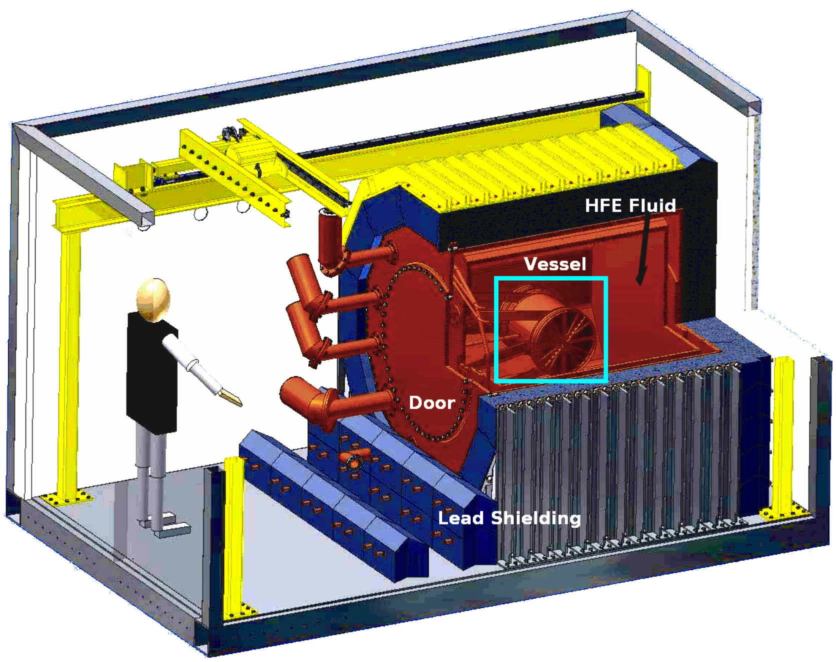

Fig 1.2: Cryostat System for EXO-200 Experiment

1.2. Neutrinoless Double Beta Decay

Neutrinoless double beta decay is a special case of beta decay. Beta decay is a common form of nuclear decay which occurs when a neutron in an unstable nucleus emits an electron and an antineutrino and becomes a proton [19].

Double beta decay occurs when a nucleus is energetically or spin forbidden to decay through single beta decay. In 1986, the first observation of double beta decay was achieved. The first experiment to observe double beta decay is EXO-200.

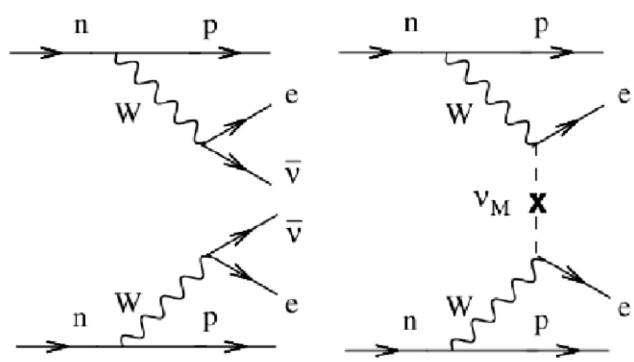

Fig.1.3: Schematic Diagram of Neutrino and Neutrinoless Double Beta Decay

Normally, if one neutron decays, it will generate a proton, an electron and an antineutrino. The left graph of Fig.1.3 shows the normal double beta decay, and two electrons and two antineutrinos are ejected from the nucleus when two neutrons decay [20, 21].

Neutrinoless double beta decay has not been observed, and this phenomenon is only predicted by theory. It is like normal double beta decay, but considering the special properties of neutrino, no neurinos would be emitted from the nucleus, which is shown by the right graph of Fig.1.3.

$$(Z, A) \rightarrow (Z + 2, A) + 2e^{-} \tag{1.1}$$

1.3. Xenon Properties

The The advantageous feature of liquid Xe are the first response of its scintillation light with a statistically sufficient amount of yield and strong stopping power of gamma rays due to its high atomic number and high density [7].

Also, since we use xenon of liquid phase, we can easily increase the detector size without losing uniformity [7].

Table 1.1 Properties of Liquid Xenon

Property Item	Unit	Value
Saturation temperature at 0.10 MPa	T (K)	164.78
Latent heat (boiling)	$\mathrm{Lv}\ (\mathrm{J/kg}) \times 10^3$	95.8
Latent heat (melting)	$\mathrm{Lv}'\ (\mathrm{J/kg}) \times 10^3$	1.2
Specific heat	$\mathrm{C}_p(\mathrm{J/kg}) \times 10^3$	0.3484
Density	$\rho(\mathrm{kg/m^3}) \times 10^3$	2.947
Viscosity	$\mu(\mathrm{Pa} - \mathrm{s}) \times 10^{-4}$	5.08
Temperature/pressure at triple point	$\mathrm{T}_t(K)/\ \mathrm{P}_t(MPa)$	161.36/0.0815

From the table, xenon has a relative density of about 3, and very narrow temperature margin between its normal boiling point and triple point [5]. So temperature control in this project becomes a very important issue. On the other hand, liquid xenon has a large latent heat of vaporization, which means liquid xenon is a good thermal buffer.

1.4. Scope of the Research

In my research, due to the limitation of space and budget, we mainly want to build up a relatively small EXO system setup, and carry small scale of experiments about xenon. It is aimed to get xenon purified and liquified, and collect extremly pure xenon in a small cell.

The reason we need extremely high-purity xenon is as follows. The wavelength of the scintillation light from liquid xenon has a central value of 174 nm in the ultraviolet region. The scintillation light is a result of photo emission from excited Xe molecules; thus, there is no absorption of the scintillation light by Xe, itself. The scintillation light, however, can be absorbed by impurities, like water and oxygen, when they contaminate in the liquid, because their photon absorption cross sections overlap the wavelength distribution of the scintillation light, causing a position dependence of the detector response. This kind of dependence is crucial for our detector, which covers a large acceptance; it is necessary to substantially reduce any impurities [7].

In our project, we use PS4-MT3-R-1, which is a Rare Gas Purifier from SAES company.

During the project, considerable amount of basic mechanical engineering knowledge was applied to set up this system.

CHAPTER 2: SYSTEM DESIGN

2.1. Overall System Design

In this project, the system is used to purify and liquefy xenon into a small cell, where later high energy experiments will be carried on. This system is described by the following graph:

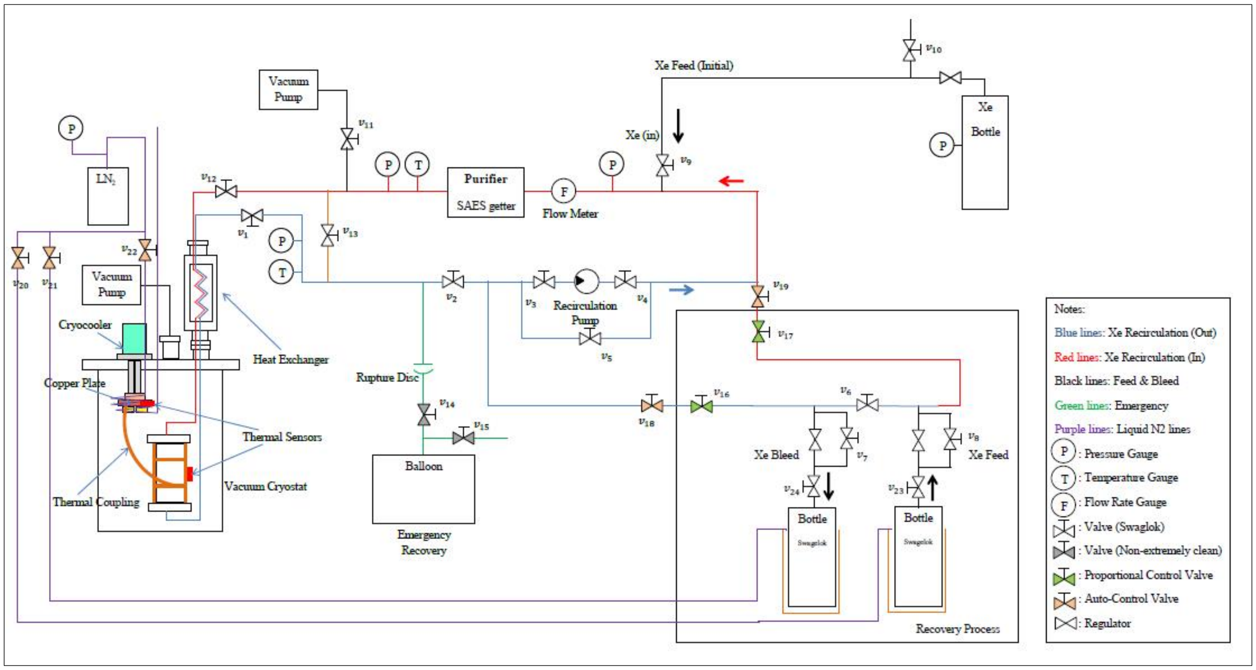

Fig 2.1: Xenon Purification and Liquefaction System Design

2.2. Description of Subsystems

From the above graph, clearly, this system can be divided into the following sub-systems:

1) Xenon Chamber. It is a sealed chamber, with cryorefrigerator, xenon experiment cell, heaters, heat-link and several thermal sensors in it [2]. The chamber will be pumped into vacuum inside, to make the inside insulated of heat transfer with the outside [12]. Also, future experiments inside the liquid xenon cell will be carried on, and additional sensors and detectors need to be added inside the small cell.

2) Heat Exchanger. It is used to reuse the cooling power, to lower the load of the cryorefrigerator. Using a heat exchanger is a good way to recuperate more than 95% of heat for evaporating Liquid Xenon to recondense the purified xenon [4, 6]. Heat exchanger will also be put in a vacuum environment, and several thermal sensors are mounted on the upper, lower, and middle position of the surface of the heat exchanger.

3) Circulation System. It is denoted by the red and blue lines. It is for xenon's circulation, and it is the part to purify xenon, and accumulate enough amount of liquid xenon in the xenon cell [11]. There are many valves, recirculation pump, purifier and many thermal and pressure sensors in it. As to the valves, we need manual valves to control the flow of xenon, and block valves to change between main circulation and feed & bleed system. Recirculation pump is used to generate pressure difference which will run the circulation. Purifier is used to pure xenon gas [13]. Pressure sensors and thermal sensors are used to reflect the status of the system, and make the system run in desired way.

4) Feed & Bleed System. It is used to inject appropriate amount of xenon when the xenon inside the circluation system is not sufficient and bleed out appropriate amount of xenon when more than enough is in the circulation system [4]. This sub-system is consist of two xenon cylinders which are used to temporarily store xenon for future feed and bleed, proportional valves to feed and bleed appropriate amount of xenon automatically, and pressure regulators which are used to adjust the inlet and outlet pressure to some valve. Two liquid nitrogen dewars are used to maintain the low temperature inside the xenon cylinders.

5) Emergency Recovery System. It is used when emergency happens, like the system is out of power, some elements are broken. Xenon is an expensive substance, we need to collect xenon when the system fails.this sub-system is consist of rupture disc which will be broken when the pressure reaches given maximum value, and a large baloon which is to store xenon temporally, and several valves to control the close or open of the Emergency Recovery System.

6) Liquid Nitrogen Loop. This part is used when the main cooling power supply, the cryorefrigerator is not working [2, 3, 5]. Since once the cryorefrigerator stops working, xenon will gradually turn to gas phase due to the increase of temperature, then the system is at high pressure, which may result in bad disasters. So we plan to use the Liquid Nitrogen Loop, to use liquid nitrogen to provide cooling power to the xenon cell, and make the system run well. The block valves, working with the three different lines, can be controlled automatically by LabView program, or be controlled by liquid level controller 286.

CHAPTER 3: MECHANICAL DESIGN

Based on what I stated in Chapter 2, the system is consist of several subsystems. Some equipemnet can be ordered directly from companies, but majority of the items need to be built by ourselves.

3.1. 3-D Modeling of System

Consider the scale of the future EXO experiments, and lots of theoretical calculation, the modeling of the system is derived. The following figure is the 3-D modeling of the entire system.

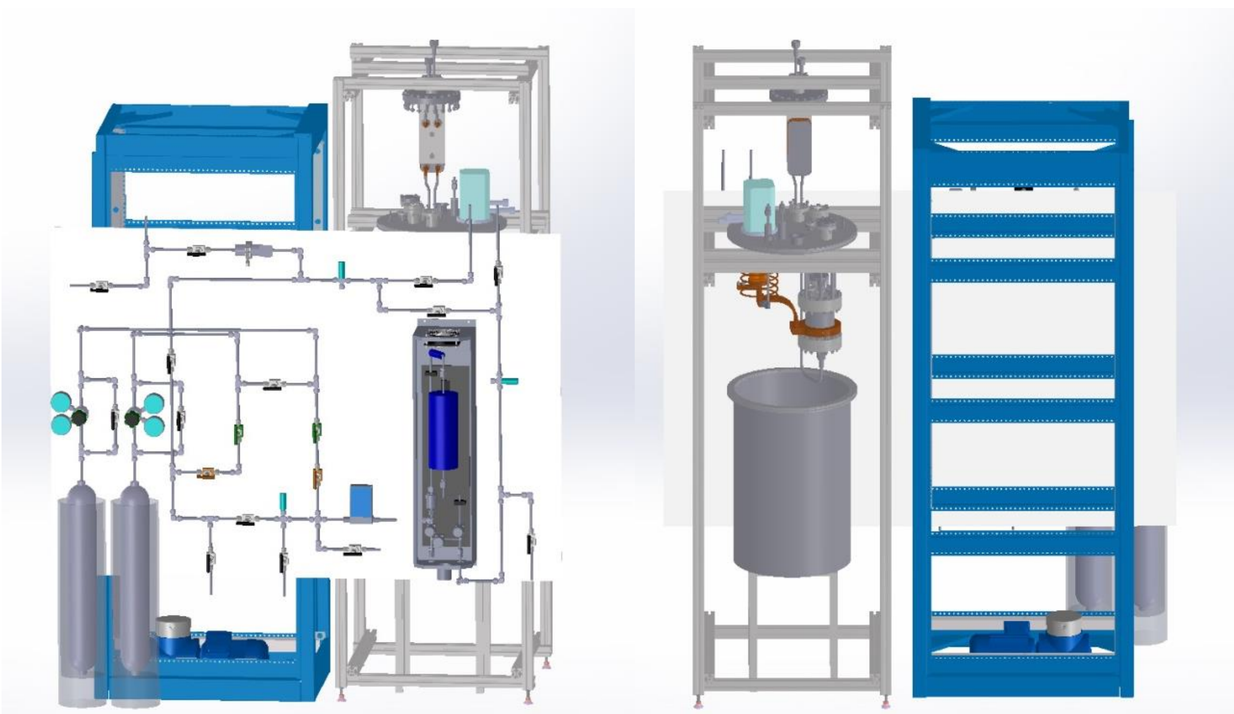

Fig. 3.1: 3-D Modeling of Entire System

The aluminum frame is used to lift the stuff inside the vacuum chamber. The two aluminum bars in the mid-height are used to lift the top plate of the vacuum chamber, and they can be moved up and down to adjust the height of the plate. The blue frame is used together with the aluminum frame to support the whole panel of the outside system [13], and a large balloon which is used to collect xenon gas when emergency happens, will be placed on the top of the blue frame [16].

All the items we ordered in this project is attached in Appendix A.

3.2. Manufacturing and Setup

Then the modeling and technique drawings were done sequently, and Nuclear Physics Lab (NPL) of University of Illinois at Urbana-Champaign will be in charge of the manufacturing of the equipment. These facilities are designed according to the standard illustated in Machinery's Handbook [26]. The following few pictures are shown about the equipment manufactured.

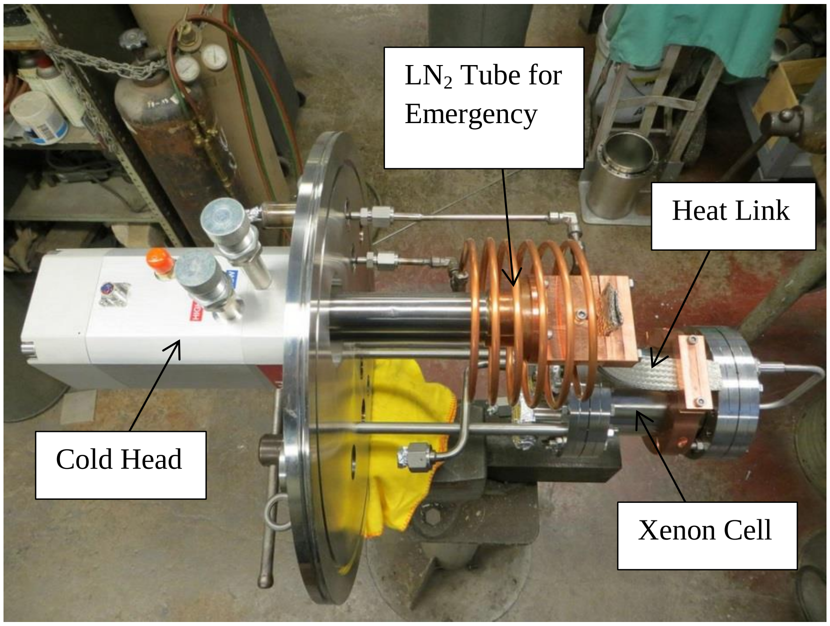

Fig. 3.2: Cold Head and Inside System

As to the heat link, which is shown in Fig. 3.2, it is made of flexible copper, since copper has a perfect heat conductivity and the shape should be changeable to connect the cold head and the xenon cell. The dimension of the heat link will be clearly stated in Chapter 5. The cold head, which is ordered from Cryomech, Inc., and is the main cooling power supply. It uses helium as the refrigerating fluid, and the temperature can reach as low as 30 K. The helical tube is used to make liquid nitrogen go through. Since the temperature of liuqid nitrogen is 77.35 K, which is far below the melting point of xenon, the heat link is also needed between helical tube and xenon cell.

On the outside surface of the xenon cell, several thermal sensors will be added, since we care about the temperature inside the cell. The temperature need to be adjusted very carefully, because the melting point (161.38 K) and boiling point (165.02 K) of xenon lie in very small temperature range.

Below is the graph for refrigerator, which works together with the cold head:

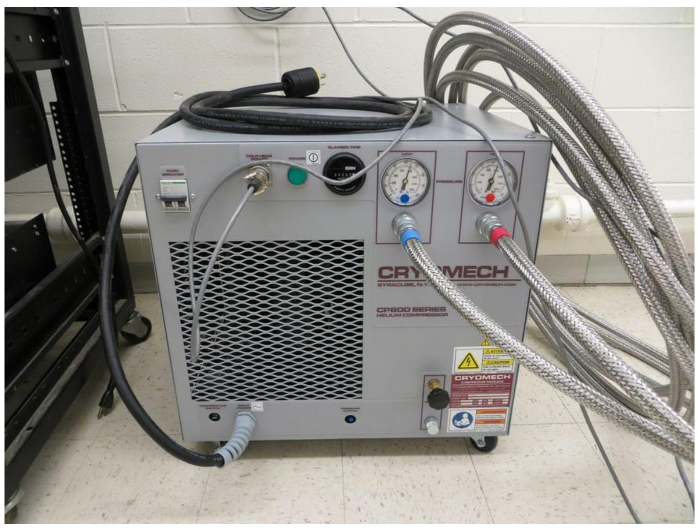

Fig. 3.3: Refrigerator Main Body

The refrigerator main body is connected with cold head using two flex lines (red for high pressure port, and blue for low pressure port). There will be helium circulation between the main body and cold head, to provide cooling power at cold head.

Fig. 3.4: Recirculation Pump

Recirculation pump is from Pfeiffer Vacuum, Inc., which is a Germany company. The pump can work from 20 Hz to 60 Hz. In the project, we use a Variable Frequency Driver (VFD) to change the running frequency of the pump.

Fig. 3.5: Heat Exchanger

Fig. 3.6: Small Vessel for Heat Exchanger

Fig. 3.5 and Fig. 3.6 shows the heat exchanger and the vessel to contain it. As I stated in Chapter 2, heat exchanger is used to improve the working efficiency of the system, and reduce the working load of the cryorefridgerator. According to the publication by Columbia University, the efficiency can be improved to 95% with the using of heat exchanger [6, 11].

Fig. 3.7: Large Vacuum Can

In Fig. 3.7, it is the large can, which used to build up a high vacuum environment. The can is made of stainless steel.The dimension of the chamber is Φ16.00” × h 24.00, with the thickness 0.2”.

The following graph, Fig 3.8, shows the connections and fittings for vacuum chamber.

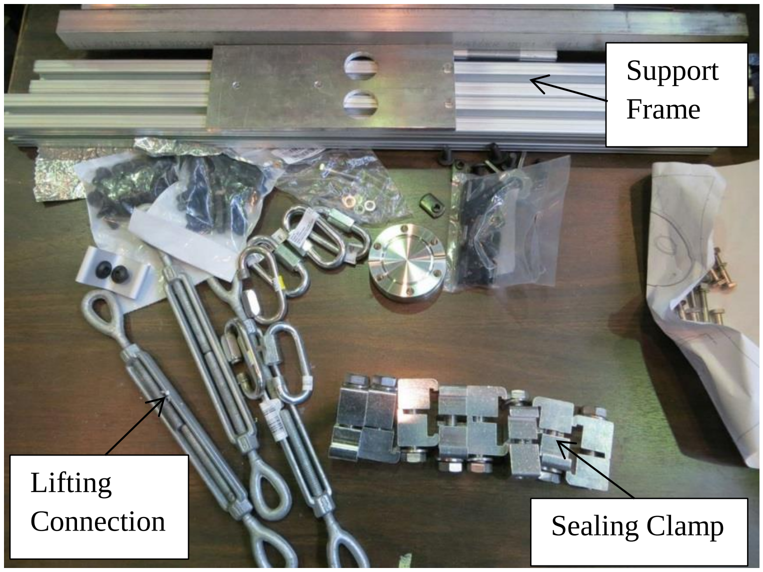

Fig. 3.8: Connections and Fittings for Vacuum Chamber

In Fig 3.8, there are several kinds of connections. The upper ones are support frames, which are used to support the upper plate of the sealed chamber. The left side are the lifting connections, which are used to lift the upper plate, and the process will be done together with chain hoist. The right side are the sealing clamps, which are used to seal the can and the upper plate together, to get the high vacuum environment.

Fig 3.9 shows the frame for the large vacuum chamber. The chain hoist is used to lift the heavy chamber upper plate.

Fig. 3.9: Frame for Vacuum Chamber and Inside System

3.3. Design and Construction of a Thermal Sensor Monitor

Since in the later experiments, we need to measure temperature at different locations to well know the system's running, then some circuits need to be built up, to work together with the thermal sensors. We have roughly 3 kinds of thermal sensors: PT 100, DT 670, and thermocouples. Thermocouples can generate voltage signal directly when place the measuring point into some temperature situation, and the voltage signal can be accepted by fieldpoint (Module: cFP-TC-120), then no further circuits need to be prepared for it. While PT 100 and DT 670, we need to build up circuits to with together with the two kinds of sensors.

PT 100 is a platinum resistance thermometers (PRT), can the measuring temperature range is from 30 K to 873 K. It is a high precise thermal sensor. Since it need some constant current for excitation, a constant current sourse has to be built up. According to the manual, the recommended excitation current is 1 mA.

DT 670, on the other hand, is a silicon diode, the measuring temperature range is from 1.4 K to 325 K. It also needs current to excite it, to give some voltage signal which corresponds to some temperature. The recommended excitation current is 10 µA ± 0.1%.

Base on the above requirement, we need to build up two kinds of circuits to provide constant current for the two different sensors. As to PT 100 and DT 670, we have two sensors for each type, so 4-channel constant current circuits are enough.

Below is the Circuits Drawing:

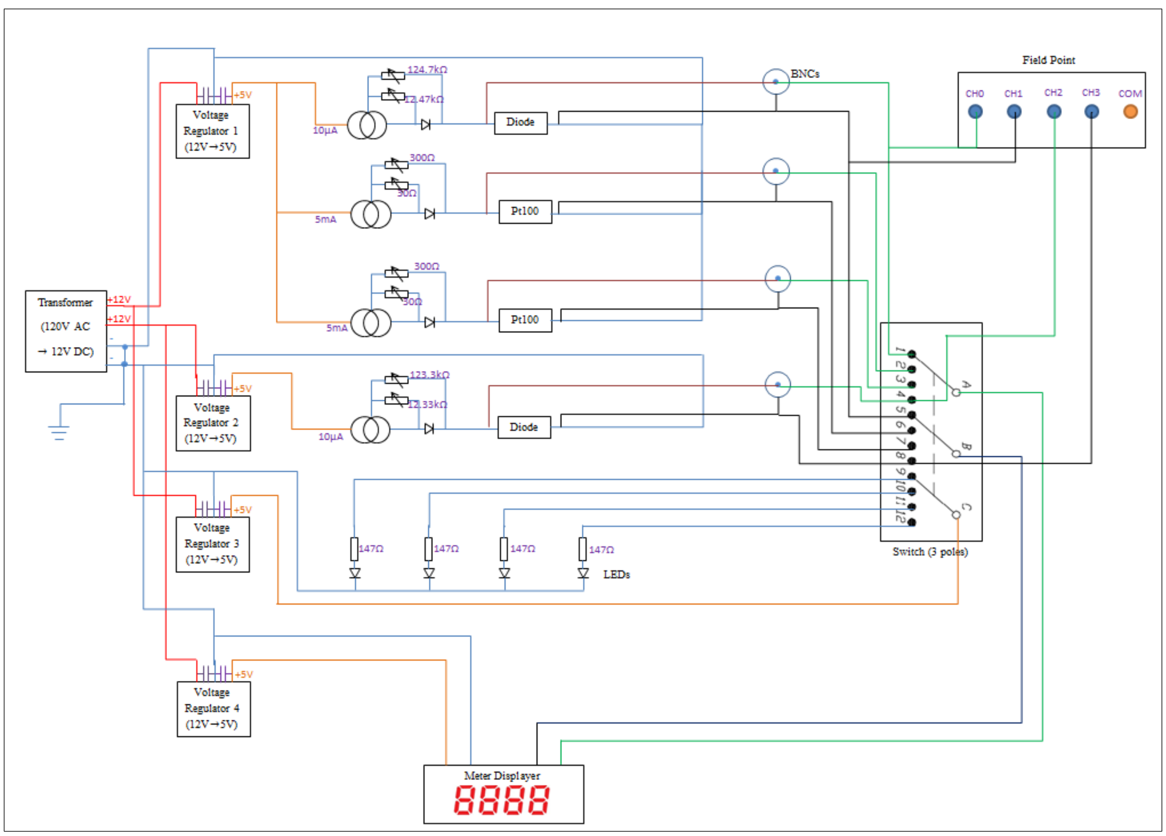

Fig 3.10: Circuit Diagram for Temperature Meter

The basic design idea of the circuits is show as below:

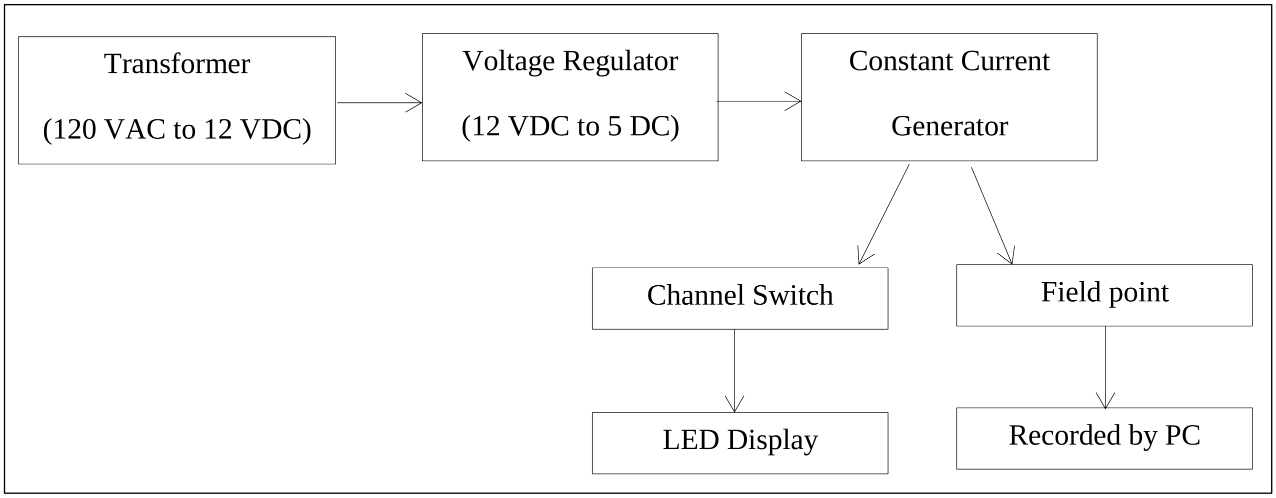

Fig 3.11: Design Idea of the Circuits Block Diagram

The testing on the breadboard is needed, to make sure the circuits work the correct way as we want. The following graph shows the testing I did.

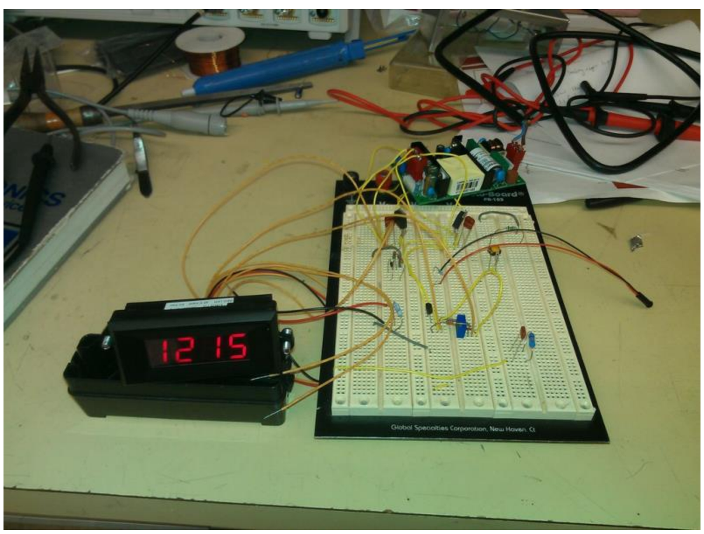

Fig 3.12: Testing of Circuits on the Breadboard

Theoretically, it should work. However, since we have multiple channels, and if the channels share one COM as voltage reference, they will interfere each others, the reason is shown below:

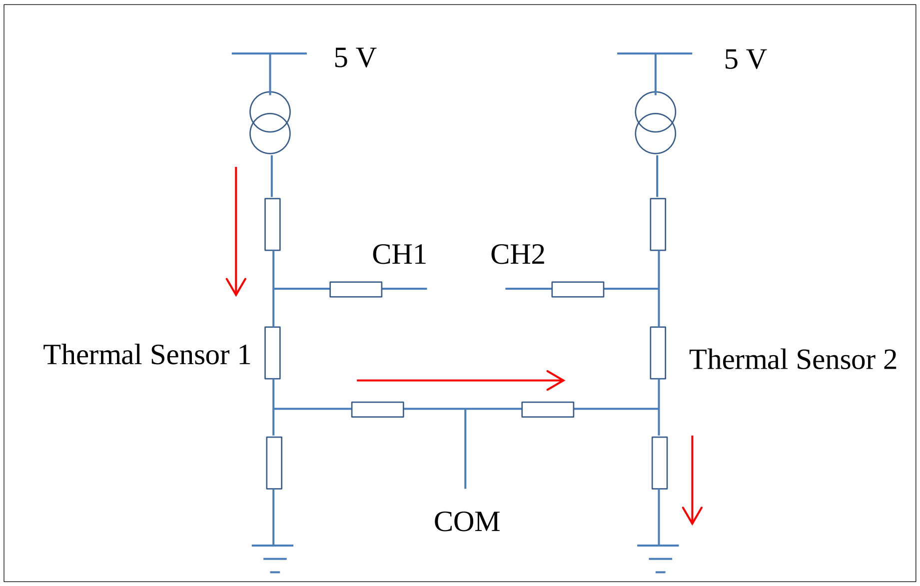

Fig 3.13: Interfering between Two Channels

Here, since the wire used in vacuum is specially made, its resistance (about 6 Ohms) can't be negligible when compared with the sensors. For example, PT 100 is about 100 Ohms at room temperature, and may reach to 20 Ohms at 77 K. Clearly, when we connect the two COMs of the two loops together, part of the current from circuit 1 (the left) will flow into circuit 2 (the right), then the voltage got from the circuits is not the voltage between the sensor, instead, it is the sum of the voltage between the sensor and the voltage between the wire, thus giving out the incorrect reading.

The testings of the two kinds of sensors were carried on many times, and the two results given by the two sensors respectively are always different, especially at very low temperature. One test result is shown in the next page:

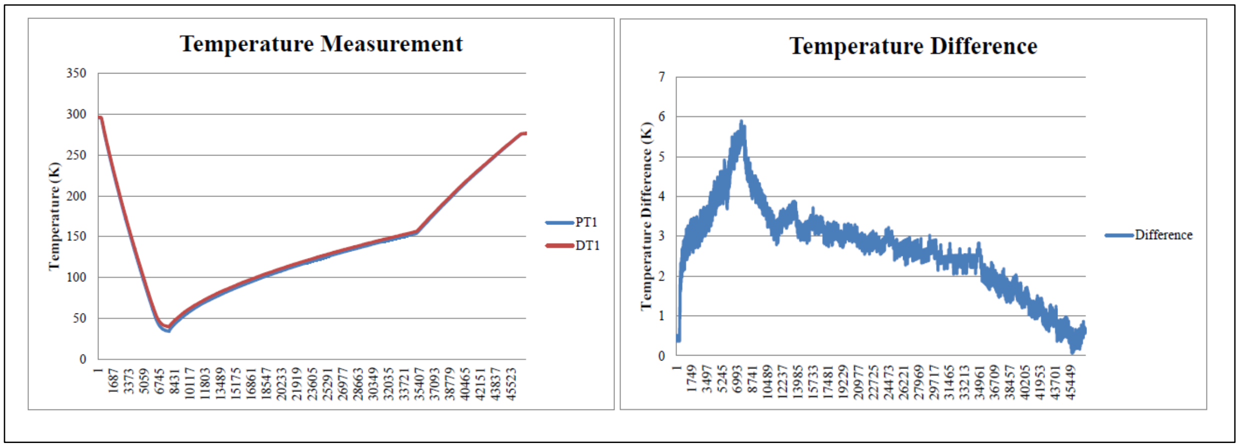

Fig 3.14: Temperatures Measured by Two Sensors

From the above graph, we can conclude that the temperature difference given by the two sensors is small when put at room temperature, and large at low temperature. It makes sense because when PT 100 is placed at low temperature environment, the corresponding resistance is very small, so the effect by the insulated wire is great.

In order to elminate the interfere between two channels, an amplifier is used to provide huge input impedance, and break the connection of the two COMs of the two channels. The pin configuration for LT1167 Amplifier is shown below:

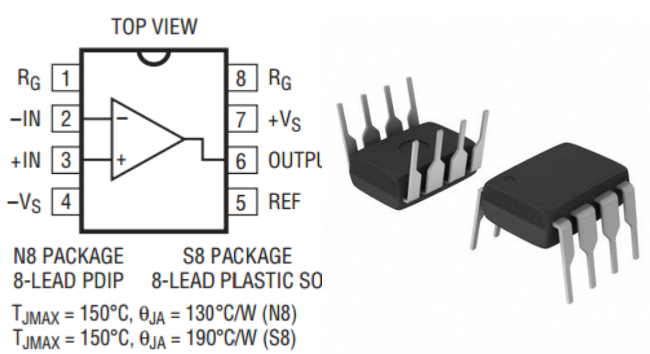

Fig 3.15: Pin Configuration of Amplifier LT1167

By testing it, we finally make the circuit work well. Then the next step is solder the chips and elements on the boards. The completed board is shown below:

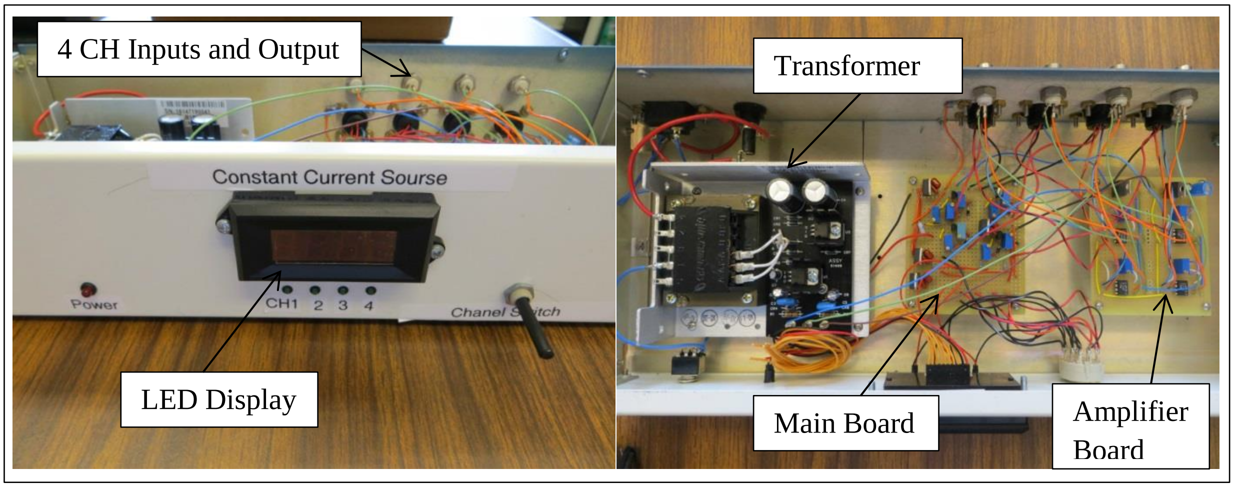

Fig 3.16: 4-Channel Self-made Circuits for Temperature Measurement

CHAPTER 4: SLOW CONTROL SYSTEM

4.1. Architecture of Slow Control System

Since there are many items in the system that require to be automatically controlled, like the proportional valves for Feed and Bleed System, block valves for Liquid Nitrogen Loop, recirculation pump, etc. Here, we use LabView as control software, to control the system's running.

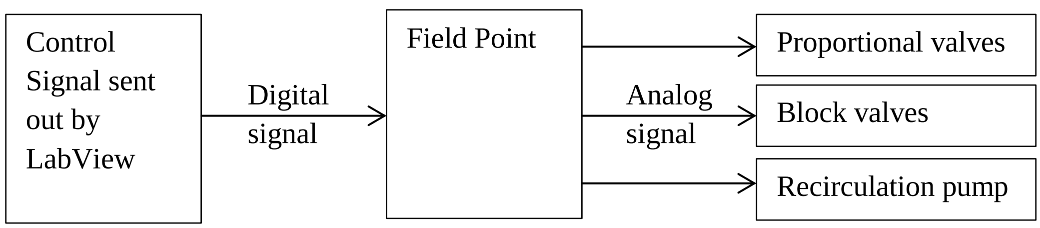

Fig. 4.1: Control Schematic Block Diagram

Besides, LabView is also used to process the signal aquired by the thermal sensors, pressure transducers, liquid level measurement sensors, flow meters, etc. Finally, LabView will display the signal in the program. The Data Acquisition (DAQ) schematic block diagram is shown below:

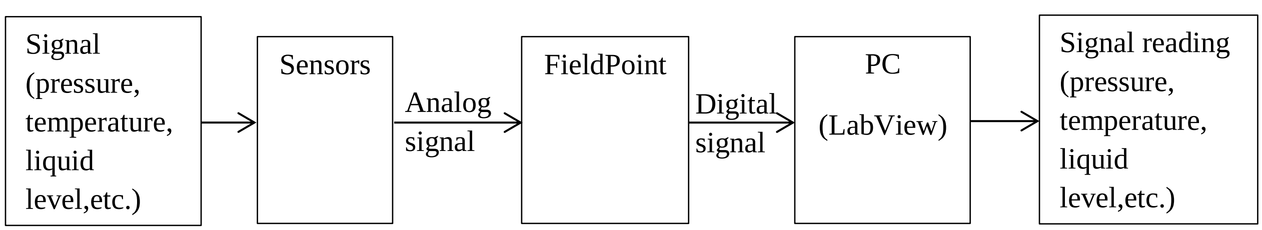

Fig. 4.2: DAQ Schematic Block Diagram

Overall, the LabView control front panel is shown below:

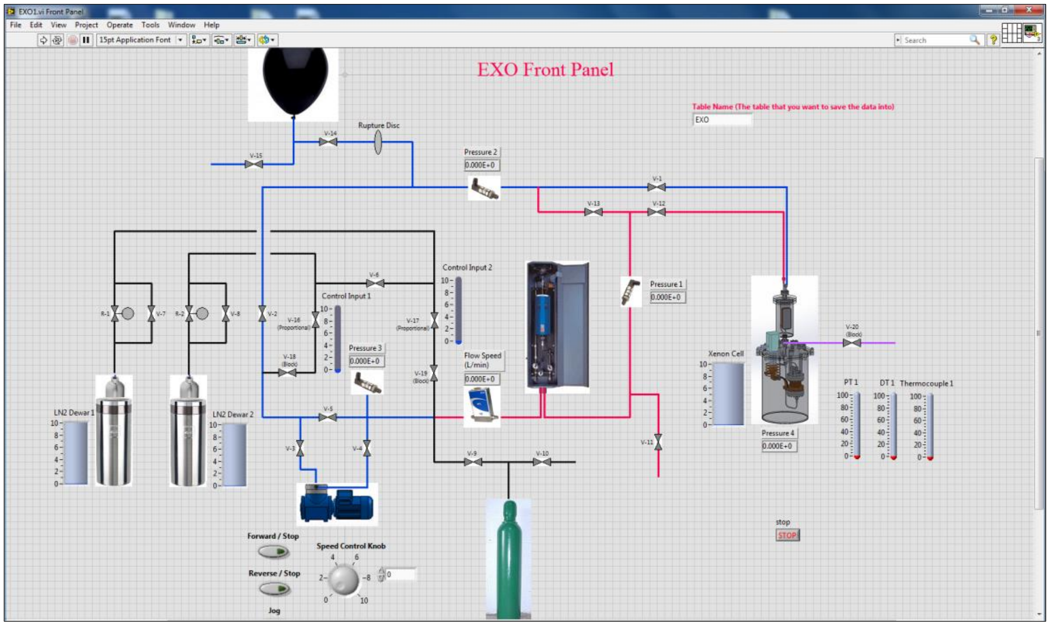

Fig. 4.3: LabView Control Front Panel (Entire System)

And the overall control block diagram is shown below:

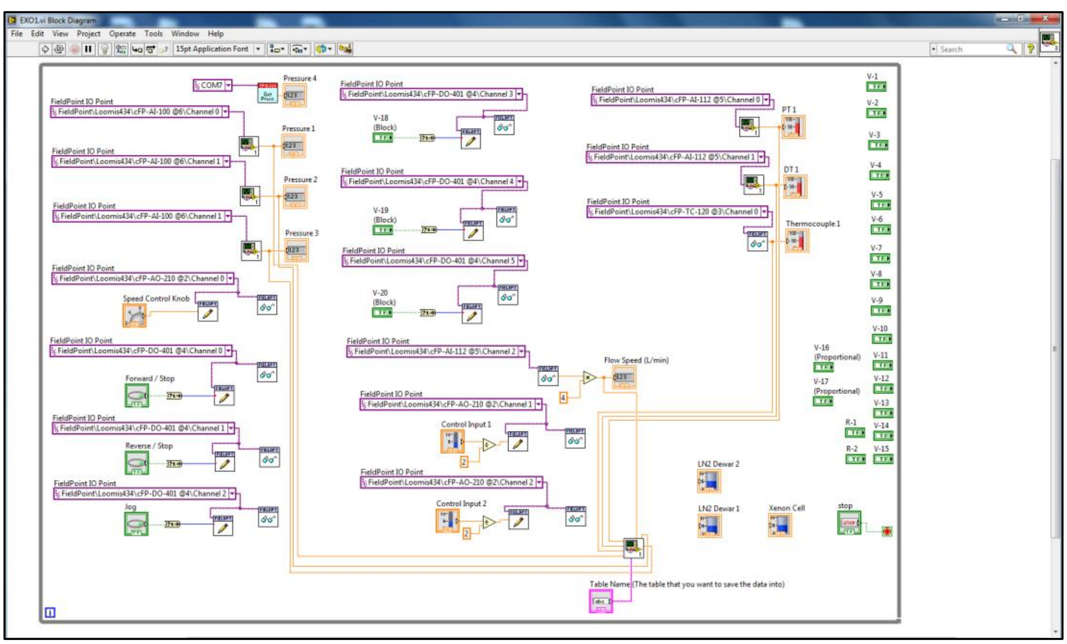

Fig. 4.4: LabView Control Block Diagram (Entire System)

Besides, LabView program will record the test data into database in MySQL. The a sub-VI is needed to save the testing data into database. The following graph shows the front panel of EXO database write sub-VI.

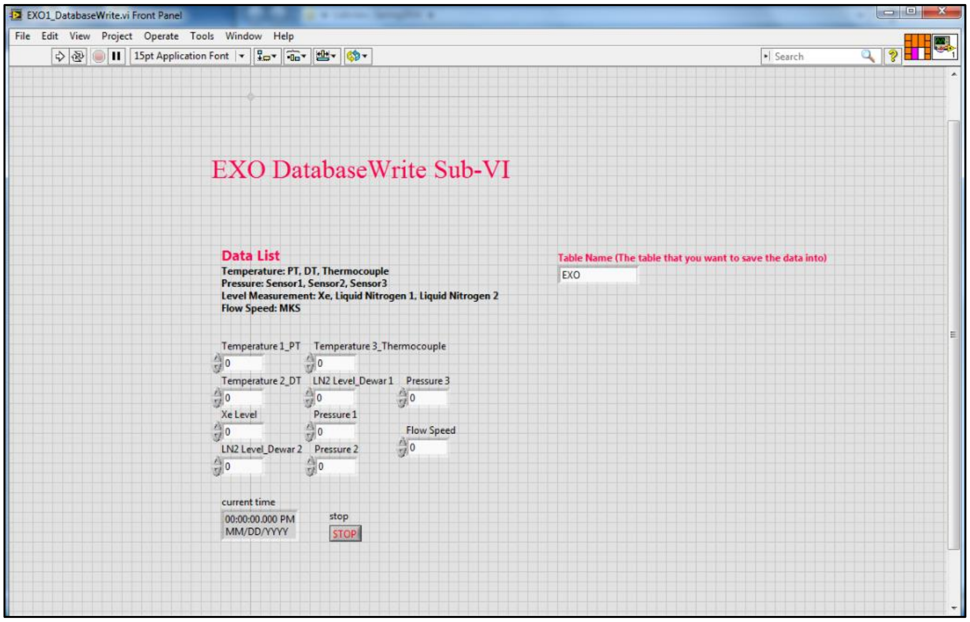

Fig. 4.5: EXO Database Write Sub-VI front panel

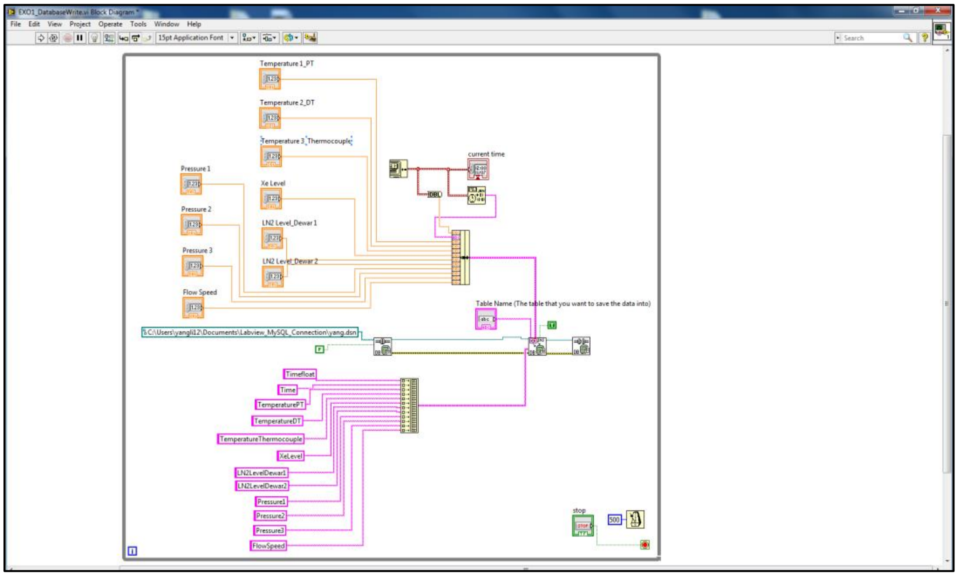

Fig. 4.6: EXO Database Write Sub-VI block diagram

In this project, we mainly care about the following signals: temperature in the vacuum chamber (measured by PT100, DT 670 and thermocouple), pressure at different positions outside the chamber (measured by 3 pressure transducers), liquid level of Xe and liquid nitrogen (measured by 3 sensors), and the flow speed (measured by MKS flow meter). Then in the sub-VI, I only write the 10 signals into database. In order to relate the data with date and time, a date & time column needs to be added in. Besides, for the displaying data of one certain time period later on, another column which convert data & time into floating number is needed, because only numbers can be compared with each other, and help to display one interval.

When we run the experiment and save the testing data into database, sometime in the future, we may want to read the data out from the database and display the plots of the previous test results, then we will need another LabView program, which can display the data and plots during the period, whose starting and ending time points can be determined by customers. Since there are about four kinds of signals, temperature, pressure, liquid level, and flow speed, then I put four plots in this LabView program, the details are shown below:

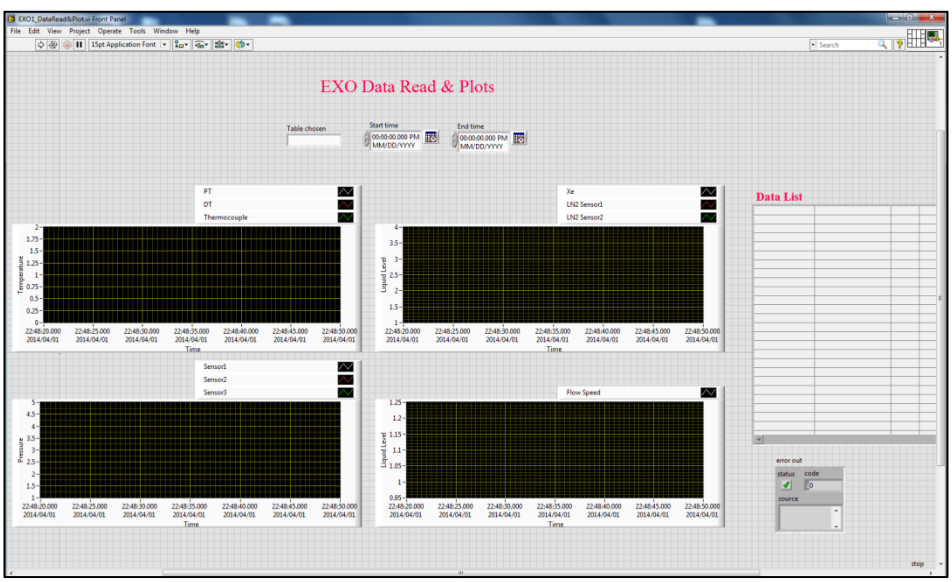

Fig. 4.7: EXO Data Read & Plots Front Panel

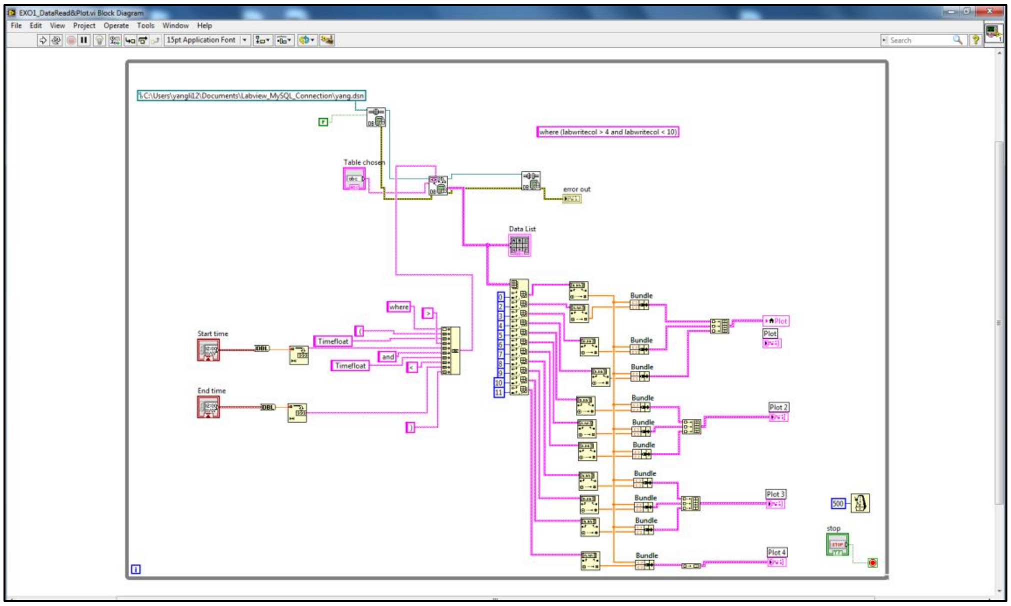

Fig. 4.8: EXO Data Read & Plots Block Diagram

If the customer wants to read the data and display the plots in some time section, the only thing he needs to do is choose the starting and ending time point, which is the time string, and the string will be converted into floating number, and use the selection criteria to find the time section between the starting and end points, and all the corresponding data will be displayed then.

4.2. Equipment Instrumentation

4.2.1. Control of Proportional Valves

Since we want to control the feed and bleed subsystem to inject or bleed right amount of xenon into or out of the system, and it is more convinient and controllable with the software LabView, so the LabView program is used to finish such task.

The proportional valves we are using is 248A-10000-RV, by MKS company. It needs to work together with a driver, 1249A. The basic idea for the control process of the proportional valve is shown in the following graph:

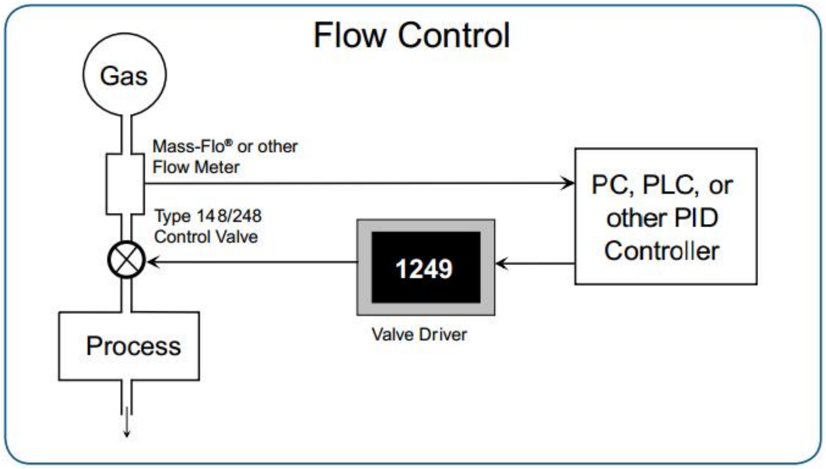

Fig. 4.9: Flow Control Schematic of Proportional Valves

In Fig. 4.9, the valve driver not only provides the power to drive the proportional valves, but also sends the control signal to the valves. Here, we use FieldPoint as the PC, PLC or other PID Controller, and use cFP-AO-210, which is the voltage output module. cFP-AO-210 will send out the control signal (0 to 5 Volts) by LabView program, and this signal will passed on to the proportional valves, and react as we want.

4.2.2. Control of Block Valves for Xenon

The Block Valves for Xenon are working together with Proportional Valves, when we want to feed or bleed some xenon, we need to use control program to turn on the block valves; while, when we don't want to change the amount of xenon inside the recirculation loop, we need to close the block valves. The purpose that we need to use block valves together with the proportional valves is that the proportional valves donnot have a very satified sealing. The basic control idea is shown in the following graph:

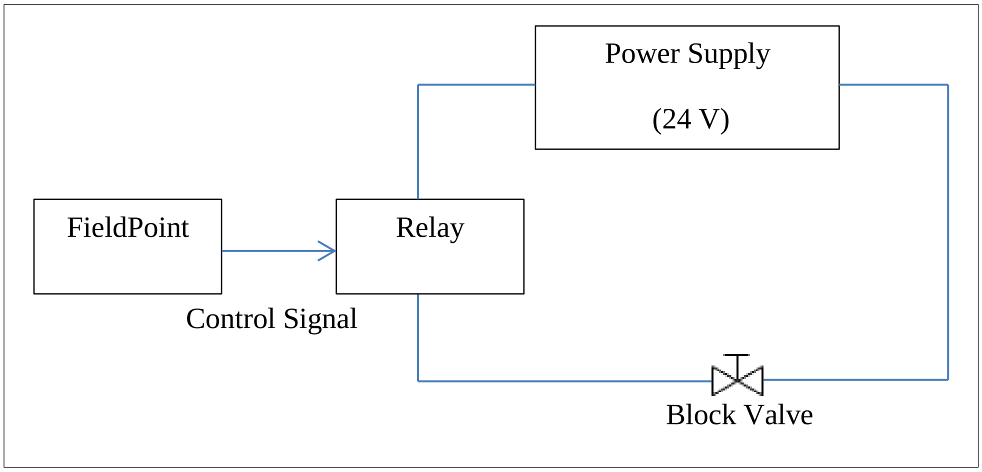

Fig 4.10: Control Schematic Block Diagram for Block Valves [Xe]

The reason that we need to use additional power supply to provide power to the valve, is that the fieldpoint is not able to provide such high power. According to the specification of the block valve, the input voltage is 24 V, and the initial current to drive the valve is 1.3 A, which is more than the fieldpoint can support. Then, an additional power supply is used and a relay acts as the switch, which is controled by fieldpoint.

4.2.3. Control of Block Valves for Liquid Nitrogen Loop

Since when the emergency happens, like the electricity failure, we have to run the Liquid Nitrogen Loop, to provide the cooling power to the inside cell. Besides, we need to feed in some amount of liquid nitrogen into the liquid nitrogen dewars, to make the xenon cylinders that are submerged in the dewars always stay in some desired temperature, to maintain the xenon in the cylinders be the liquid phase.

The control of the Block Valves for Liquid Nitrogen Loop is similar with the situation of Block Valves for Xenon. One difference is Level Measurement Sensors will tell the level of liquid nitrogen, then we can use the feedback of Level Measurement System to control the liquid nitrogen's flow and its amount. Since the level controller can provide enough power for the block valves to work well, no need to use

LabView program to do that. The following graph is shown the schematic block diagram for block valves for liquid nitrogen.

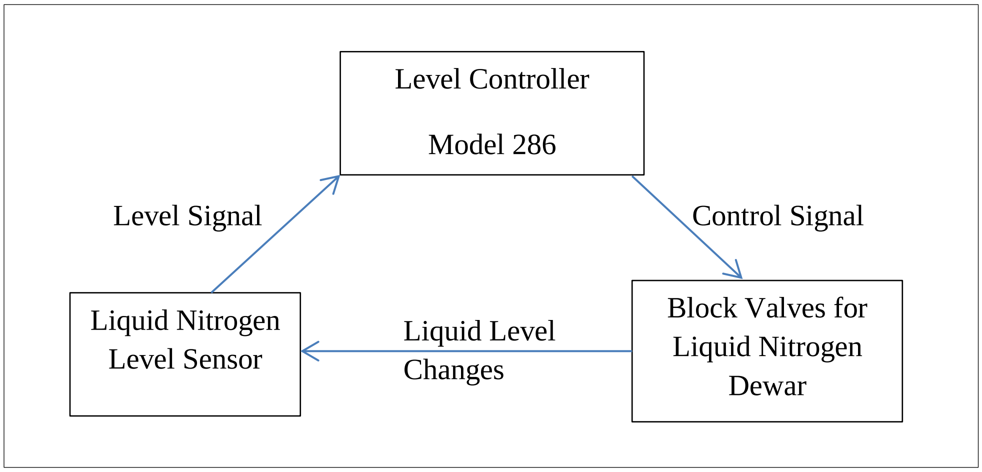

Fig 4.11: Control Schematic Block Diagram for Block Valves (Liquid Nitrogen)

4.2.4. Control of Recirculation Pump

The pump is used to generate a reasonable pressure drop and run the xenon recirculation. The pressure drop it can generate is about half atmosphere. The pump we use is diaphragm-gas sampling pump, Part Number PM26866-143.12, from KNF Inc. The control schematic block diagram is shown below:

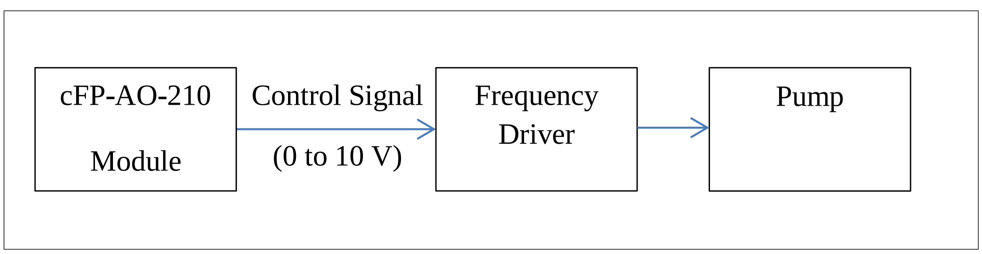

Fig 4.12: Control Schematic Block Diagram for Pump

The control signal will be given by turning the Speed Control Knob by customers, to change the speed of the pump. Also, the program can help custom to make the pump running Forward/Stop, Reverse/Stop, and Jog. The direct change between Forward and Reverse is forbidden, to protect the pump.

4.2.5. Temperature Measurement and Thermal Sensor Testing

In the project, we care about the temperatures at different locations of the system, especially we need to know the temperature inside the vacuum can to better know how the system is running. In fact, three thermal sensors are mounted at different locations on the heat exchanger; three sensors are mounted on the top, middle, and bottom of the xenon cell; two other sensors are mounted on the cold head.

As stated in the previous chapters, three kinds of thermal sensors are used. As to PT 100 and DT 670, the relationship between resistance and temperature (for PT 100), and the relationship between output voltage and temperature (for DT 670) are given by company. Two functions for PT 100 and DT 670 are needed to derived from the sensor response data. The block diagram of this idea is shown below:

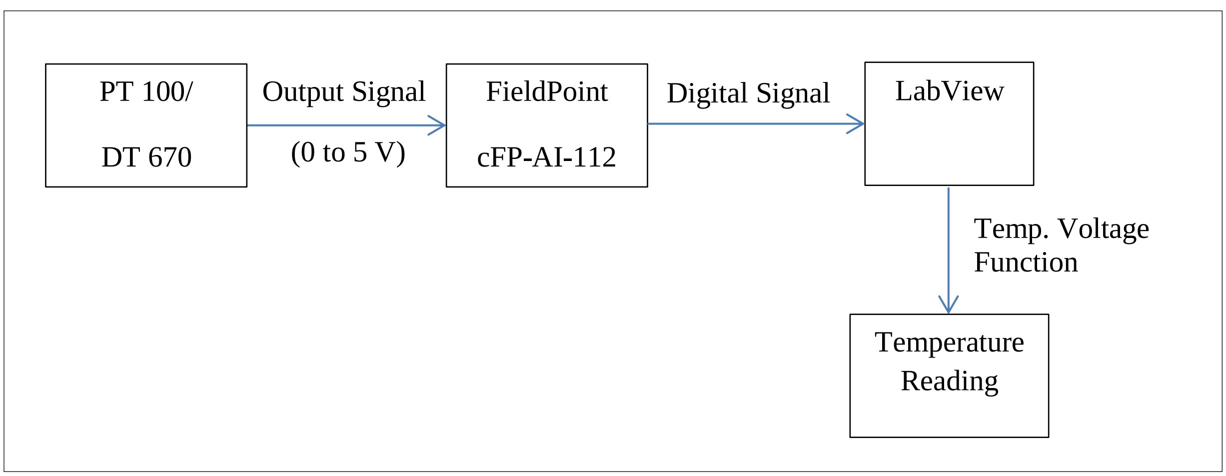

Fig 4.13: Schematic Block Diagram for PT 100 and DT 670

Besides PT 100 and DT 670, the third kind of thermal sensor is thermocouple. The thermocouple in this project is T type, with temperature range from 23 K to 623 K. The data acquisition block diagram is relatively easy, compared with PT 100 and DT 670, because no temperature function of voltage is needed. The schematic block diagram is shown below:

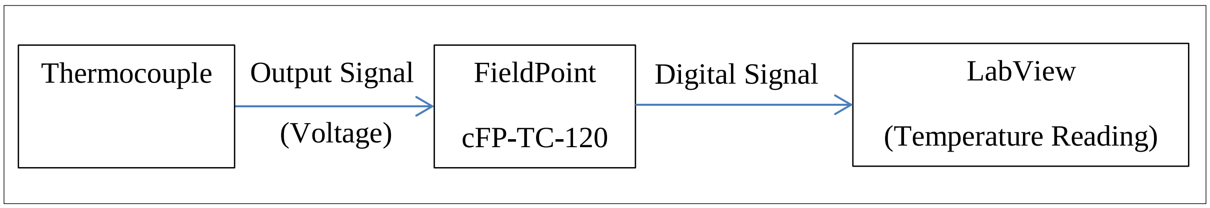

Fig 4.14: Schematic Block Diagram for Thermocouple

4.2.6. Pressure Measurement

Similar with temperature, we need to get the pressure signal of the system, to make sure the system is running in a desired way. In the outside recirculation loop, three pressure transducers are used. The output of the pressure transducers is current (4 mA to 20 mA), which corresponds to pressure range (0 to 30 psi), with a proportional relationship.

The schematic block diagram is shown below:

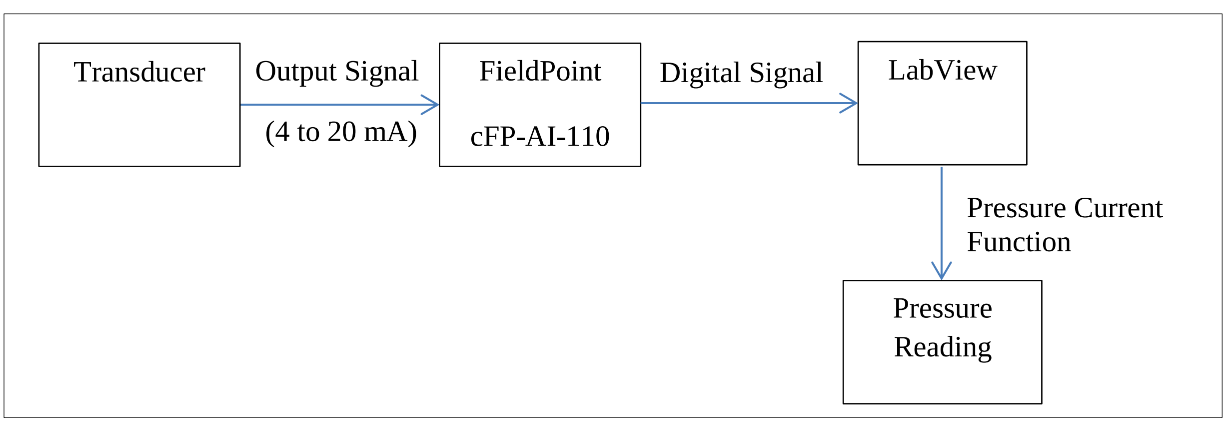

Fig 4.15: Schematic Block Diagram for Pressure Transducer

4.2.7. Liquid Level Measurement

Liquid level is also a kind of parameter we care about. From the Xe liquid level sensor, we can know how much xenon inside the vacuum chamber, because we can’t see directly into what the level inside the chamber. Base on that, we may control the bleed and feed system, to react as it needs.

From the liquid nitrogen level sensors, we can know how much liquid nitorgen is in the dewars. More importantly, the liquid nitrogen level, is a signal that is needed to control the Xe block valves, to maintain a correct temperature range for Xe cylinders.

The following graph is shown about how the level signal is processed.

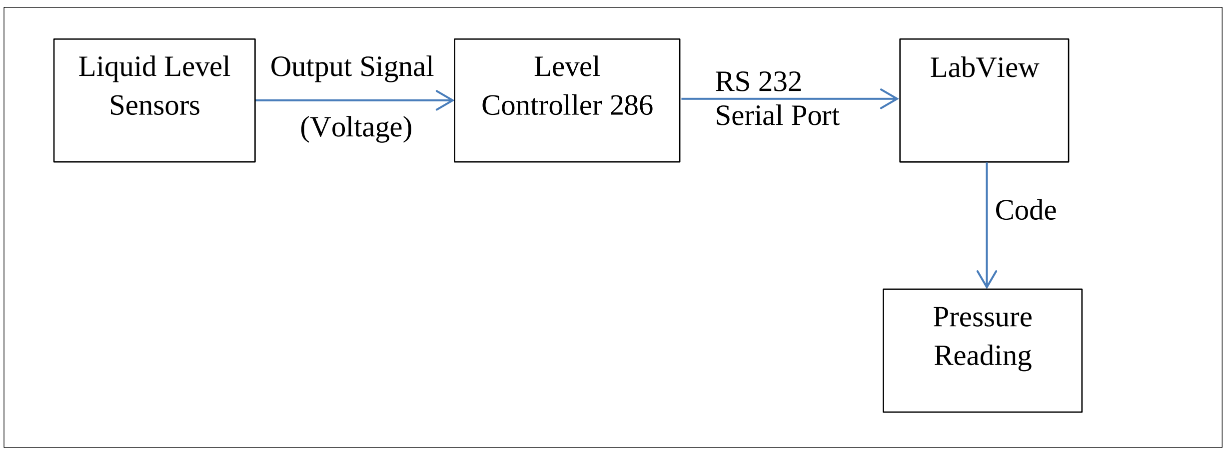

Fig 4.16: Schematic Block Diagram for Liquid Level Sensors

4.3. Slow Control Database Setup

When we run the experiments, we also need to record and store the data into some database. In this project, we use MySQL as the database software, because it is more reliable than only save the test data into excel files.

MySQL is an open-source relational database management system (RDBMS), and ships with no GUI tools to administer MySQL databases or manage data contained within the databases. Users may use the included command line tools, or use MySQL "front-ends", desktop software and web applications that create and manage MySQL databases, build database structures, back up data, inspect status, and work with data records.

In this project, we need to use different sensors to measure the parameters of the system, like pressure, temperature, and liquid level; then the signal will be sent to FieldPoint, and be converted into digital signal; and LabView will read out the signal, and save the data into database. The process is shown in the following graph:

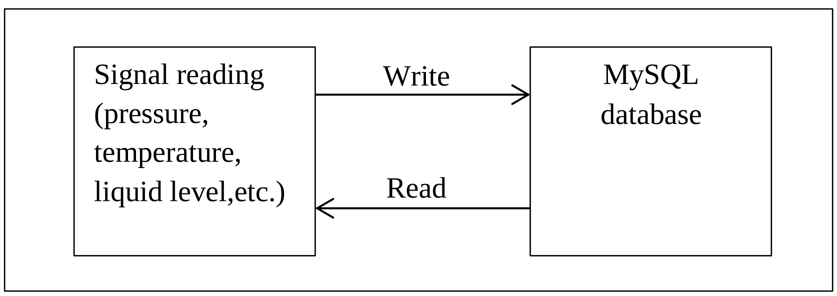

Fig. 4.17: Database Write and Read Schematic Block Diagram

Besides that we need to write the data into MySQL for record and store, we also need to use LabView to read the data from database, to get to know the previous experimental results.

The database write part is shown in Fig 4.5 and Fig 4.6, and database read part is shown in Fig 4.7 and Fig 4.8.

The following graph shows the data that is saved in database in MySQL. Each signal will be saved in one column. Column 1 is the floating number corresponding to a certain time point, which is used for the later searching a period of time section that we are interested in.

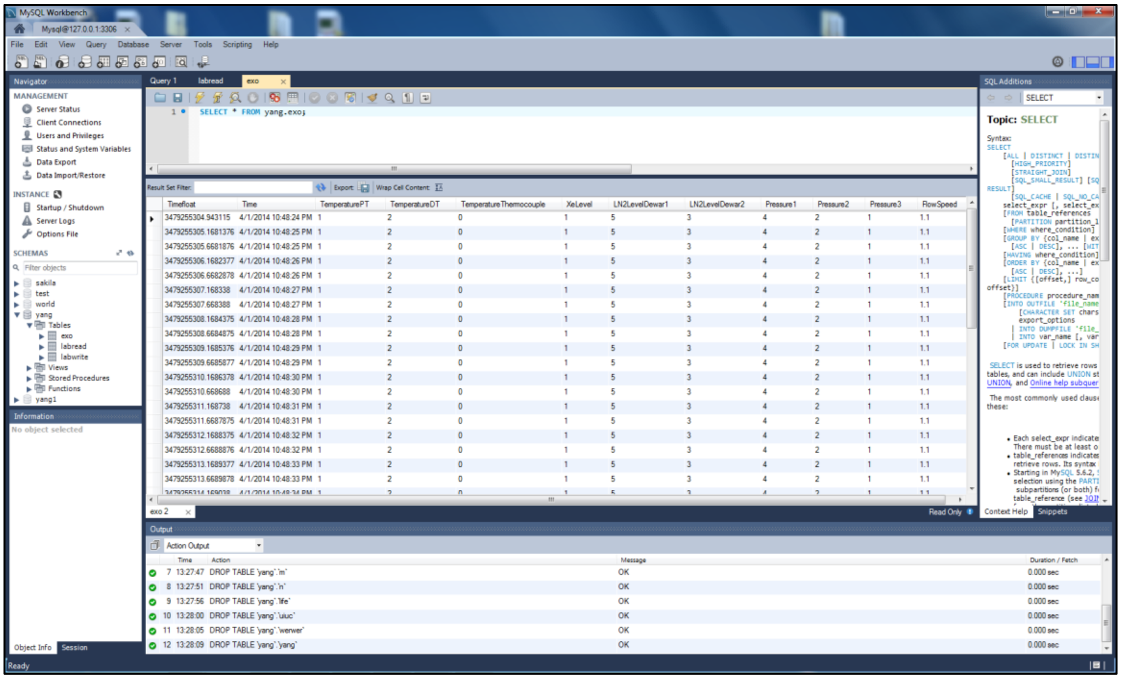

Fig 4.18: Data Saved in Database in MySQL

For different time period of experiments, we can save the data into different databases, which are listed in the section on the left. The data achieved from experiment can’t be modified, to protect the original data of the experiments. The tables can also be displayed in the front panel in MySQL, and connections between the tables will clearly describe their internal relationship. In this project, since we can use LabView to write into the database, and use LabView to read out from the database, then there is no need to display the data in the front channel. The only purpose of the database in MySQL is used to store data.

CHAPTER 5: XENON FLOW AND THERMODYNAMIC CALCULATION

During the project, we need to decide the dimension of several containers, heat exchanger, and recirculation tubes, etc. In Chapter 5, theoretical calculation about dimension of recirculation tube, size of heat exchanger, dimension of liquid nitrogen dewars, and consumption speed of liquid nitrogen when the cryo-refrigerator will be stated.

5.1. Dimension of Recirculation Tube

The system running conditions are given below:

1) The delivery rate is 20 L/min at 1 atm.
2) The pressure drop we want is 0.5 atm (i.e. 50662.5 Pa).
3) Most of the tubes are outside, considering the room temperature, 293.15 K.
4) Consider 1 atm pressure of Xenon inside the tube.

5.1.1. Route Loss Calculation:

First, let's consider the long straight tube without any other things, like the gauge, the turnings, crossings, etc.

Suppose that we choose the outside diameter of the tube is 0.5inch (suppose the inside diameter is 0.402inch), then the flow rate is

$$V = \frac{4Q}{\pi d^2} = \frac{4 \times \frac{20 \times 10^{-3}}{60}}{\pi \times (0.402 \times 0.0254)^2} = 4.07 m/s \tag{5.1}$$

Reynolds number

$$Re = \frac{\rho V d}{\mu} \tag{5.2}$$

ρ denotes density of the fluid, V denotes velocity, d denotes the characteristic length (diameter for tube), μ denotes viscosity.

For $Re < 2300$, it is laminar flow; for $Re > 2300$, it is turbulent flow.

When velocity of the fluid is much smaller, it can be treated as the incompressible fluid.

Tube laminar flow pressure drop

$$\Delta p_\lambda = \frac{128\mu l}{\pi d^4} q \tag{5.3}$$

The viscosity of xenon at different temperature is given in Table 5.1 and Fig. 5.1 [22].

Table 5.1 Viscosity of Xenon

Temperature (K)	Viscosity (Pa$\cdot s$)
273	21.2×10^{-6}
300	23.2×10^{-6}

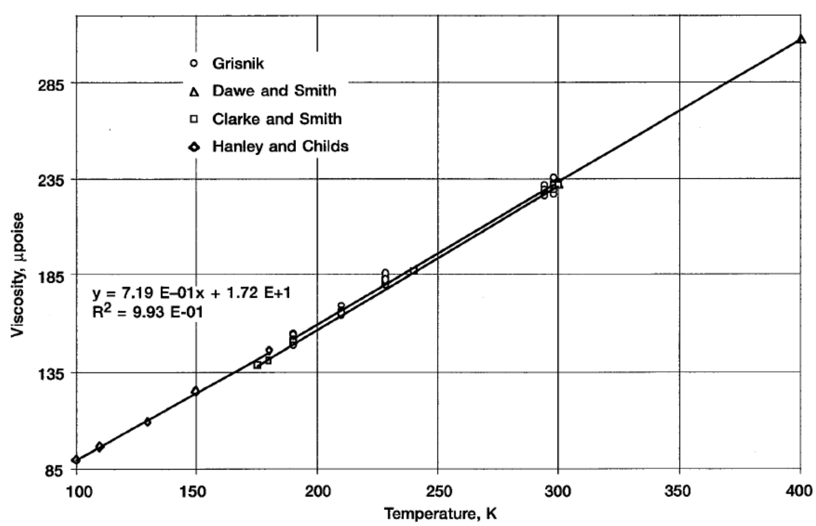

Fig. 5.1 Viscosity of gaseous Xenon vs Temperature, 700-760 Torr.

We can get the relationship between viscosity and temperature is as follows:

$$\mu(t) = 0.6725t + 30.25 \tag{5.4}$$

$$\mu(293.15K) = 22.7 \times 10^{-6} Pa \cdot s \tag{5.5}$$

$$\rho(293.15K) = 5.887 kg/m^3 \tag{5.6}$$

$$Re(293.15K) = \frac{\rho V d}{\mu} = \frac{5.887 \times 4.07 \times 0.402 \times 0.0254}{22.7 \times 10^{-6}} = 10777 \tag{5.7}$$

When the temperature is a bit greater than 162K, i.e. the outside of cryostat, the corresponding Re will be greater than 10777 by a little bit.

For clean steel pipe or aluminum pipe, absolute roughness is [23]:

$$e = 0.0015 \sim 0.01 \tag{5.8}$$

Here, we use 0.005, without losing the generality.

So we get:

When $Re > 2300$, there are different empirical formulas according to different Re ranges.

For $4000 < Re < 10^5$, which is called hydraulic smooth, using Blasius formula [23],

$$\lambda = \frac{0.3164}{Re^{0.25}} = \frac{0.3164}{10777^{0.25}} = 0.0311 \tag{5.9}$$

So the pressure drop is

$$\Delta p_\lambda = \lambda \frac{L}{D} \rho \frac{V^2}{2} = 0.0311 \times \frac{L}{0.0254 \times 0.402} \times 5.887 \times \frac{4.07^2}{2} < 0.5 \times 101325 \tag{5.10}$$

Then, we get:

$$L < 341m \tag{5.11}$$

This length is long enough in the ideal situation.

Next, let's consider another situation: the outside diameter of the tube is 0.25inch (the inner diameter is assumed also 0.25 inch), then the flow rate is

$$V = \frac{4Q}{\pi d^2} = \frac{4 \times \frac{20 \times 10^{-3}}{60}}{\pi \times (0.25 \times 0.0254)^2} = 10.52m/s \tag{5.12}$$

$$\rho(293.15K) = 5.887kg/m^3 \tag{5.13}$$

$$Re(293.15K) = \frac{\rho V d}{\mu} = \frac{5.887 \times 10.52 \times 0.25 \times 0.0254}{22.7 \times 10^{-6}} = 17324 \tag{5.14}$$

$$\lambda = \frac{0.3164}{Re^{0.25}} = \frac{0.3164}{17324^{0.25}} = 0.0276 \tag{5.15}$$

So the pressure drop is

$$\Delta p_\lambda = \lambda \frac{L}{D} \rho \frac{V^2}{2} = 0.0276 \times \frac{L}{0.0254 \times 0.25} \times 5.887 \times \frac{10.52^2}{2} < 0.5 \times 101325 \tag{5.16}$$

$$L < 35.78m \tag{5.17}$$

The length is not long enough, if we consider the thickness of the tube, then the maximum length will be shorter. So 1/4" may be not sufficient.

Then, consider the 3/8" diameter, suppose the inside diameter is 0.305 inch, then the flow rate is

$$V = \frac{4Q}{\pi d^2} = \frac{4 \times \frac{20 \times 10^{-3}}{60}}{\pi \times (0.305 \times 0.0254)^2} = 7.07m/s \tag{5.18}$$

$$Re(293.15K) = \frac{\rho V d}{\mu} = \frac{5.887 \times 7.07 \times 0.305 \times 0.0254}{22.7 \times 10^{-6}} = 14204 \tag{5.19}$$

$$\lambda = \frac{0.3164}{Re^{0.25}} = \frac{0.3164}{14204^{0.25}} = 0.029 \tag{5.20}$$

So the pressure drop is

$$\Delta p_{\lambda} = \lambda \frac{L}{D} \rho \frac{V^2}{2} = 0.029 \times \frac{L}{0.0254 \times 0.305} \times 5.887 \times \frac{7.07^2}{2} < 0.5 \times 101325 \tag{5.21}$$

$$L < 92m \tag{5.22}$$

This length should be enough, even if we take other factors that may make the pressure drop larger.

5.1.2. Local Loss Calculation

However, there are many valves, meter gauges and other elements in the circuit. Also, change of the tube direction will also increase the pressure drop. To accurately calculate the pressure drop, more information about the circuit need be given, like the valve type, angle of tube direction change, etc [23].

As to the local pressure loss,

$$\Delta P_{\zeta} = \zeta \frac{\rho v^2}{2} \tag{5.23}$$

here, ζ is local resistance coefficient.

As to entrance and exit, we also need to consider local pressure loss. For entrance [24],

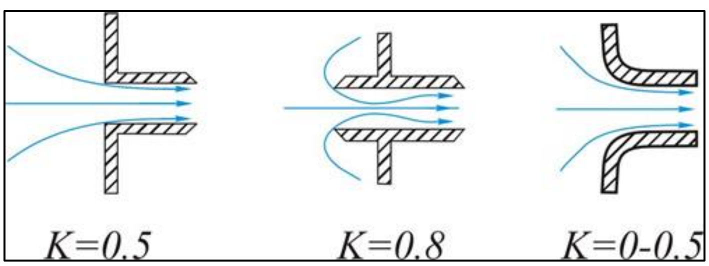

Fig 5.2: Local Resistance Coefficient of Entrance and Exit

In our project, we need to consider the third situation. And since the tubes and other equipment are in good conditions, the local resistance coefficient is chosen to be 0.2, without losing generality.

- For tube 3/8”:

$$\Delta P_{\zeta entr} = \zeta \frac{\rho v^2}{2} = 0.2 \times \frac{5.887 \times (7.07)^2}{2} = 29.43Pa \tag{5.24}$$

- For tube 1/2":

$$\Delta P_{\zeta entr} = \zeta \frac{\rho v^2}{2} = 0.2 \times \frac{5.887 \times (4.07)^2}{2} = 9.75Pa \tag{5.25}$$

Then the local loss at exit also needs to be considered. For exit:

$$\zeta = 1 \tag{5.26}$$

- For tube 3/8”:

$$\Delta P_{\zeta exit} = \zeta \frac{\rho v^2}{2} = \frac{5.887 \times (7.07)^2}{2} = 147Pa \tag{5.27}$$

- For tube 1/2":

$$\Delta P_{\zeta exit} = \zeta \frac{\rho v^2}{2} = \frac{5.887 \times (4.07)^2}{2} = 48.8Pa \tag{5.28}$$

According to the knowledge of Fluid Mechanics, there is pressure drop when fluid flows through valves, then local lose caused by valves also need to be considered.

Below is the table of Valve Loss Coefficient for the common valves [24]:

Table 5.2 Valve Loss Coefficient K

Type of Valve		Range of Valves	Representative Valves
Multi-turn Valves			
Diaphragm	-	1.0 to 3.0	2.0
Gate	Full port	0.1 to 0.4	0.2
	Reduced port	0.5 to 1.3	0.8
Globe	Standard	2 to 10	3.5
	60º Y-pattern	1.5 to 4	2.5
	45º Y-pattern	1.0 to 3.0	1.6
	Angle	2 to 5	4
Pinch	-	1 to 2	1.5
Needle	-	3 to 15	6
Quarter-Turn Valves			
Ball	-	1.0 to 3.0	2.0
	Full port	0.1 to 0.4	0.2
Butterfly	Reduced port	0.5 to 1.3	0.8
Plug	Standard	2 to 10	3.5
	60º Y-pattern	1.5 to 4	2.5
Self-Actuated Valves	45º Y-pattern	1.0 to 3.0	1.6
Check	Angle	2 to 5	4
	-	1 to 2	1.5
	-	3 to 15	6

According to the design, in the longest loop, we have about 6 gate valves, 1 check valve and 1 relief valve.

- For tube 3/8”:

$$\Delta P_{\zeta val} = \Sigma\, \zeta \frac{\rho v^2}{2} = (1.2 + 2.4 + 1.5) \times \frac{5.887 \times (7.07)^2}{2} = 750.4Pa \tag{5.29}$$

- For tube 1/2”:

$$\Delta P_{\zeta val} = \Sigma\, \zeta \frac{\rho v^2}{2} = (1.2 + 2.4 + 1.5) \times \frac{5.887 \times (4.07)^2}{2} = 248.7Pa \tag{5.30}$$

Next, let’s consider the local loss through elbows due to the direction change of tubes.

For the direction change of the tube, consider 90^o elbow, which is shown below [24]:

Table 5.3 Local Loss Coefficient (90º Elbow)

R/d	0.5	1.0	1.5	2.0	3.0	4.0	5.0
ξ	1.20	0.80	0.60	0.48	0.36	0.30	0.29

Here, we consider 15 elbows, and take $\frac{R}{d} = 1.5$, then $\zeta = 0.6$,

- For tube of 3/8”:

$$\Delta P_{\zeta el} = \zeta \frac{\rho v^2}{2} = 15 \times 0.6 \times \frac{5.887 \times (7.07)^2}{2} = 1324.2Pa \tag{5.31}$$

- For tube of 1/2”:

$$\Delta P_{\zeta el} = \zeta \frac{\rho v^2}{2} = 15 \times 0.6 \times \frac{5.887 \times (4.07)^2}{2} = 438.8Pa \tag{5.32}$$

Finally, we still have other facilities that cause the local loss, like heat exchanger, purifier, gauges, etc.

As to the heat exchanger, the pressure drop is not given. But for other products from the same company, it gives the pressure drop (usually large) when the fluid is liquid and at high pressure situation (20atm). When the fluid is gas and operated at low flow speed, personally, the pressure drop should be small.

As to the purifier, I didn’t find the manual talks about its pressure drop. Here, I have to put it negligible.

As to the gas meter, the pressure drop depends on the valves, usually it is not large; as to one kind of valve, the pressure drop is 150Pa at 200L/min. Since the flow speed is only 20L/min in our situation, the pressure drop should be less. Here I use 100Pa.

After considering all the possible reason that causes the local loss, we can decide the dimension of the tube to meet the requirement of our project.

- For tube 3/8”, all pressure drops by the local loss

$$\Delta P_\zeta = 29.43 + 147 + 750.4 + 1324.2 + 200 = 2451 Pa \tag{5.33}$$

- For tube 1/2”, all pressure drops by the local loss

$$\Delta P_\zeta = 9.75 + 48.8 + 248.7 + 438.8 + 200 = 946 Pa \tag{5.34}$$

Considering the local loss, we can calculate the length of the tubes for tube 3/8” and tube 1/2":

$$l_{3/8"} = 87 m \tag{5.35}$$

$$l_{1/2"} = 336m \tag{5.36}$$

Additionally, since we don't know the pressure drop through heat exchanger and purifier very well, also there may be some other unexpected pressure loss. Generally, the 1/2" tube can for sure meet the requirement; the 3/8" tube can work well if there is no large pressure drop through heat exchanger and purifier (should be small, according to the information given by the companies).

Additionally, we can make the pressure difference of the pump larger, 0.5 atm is a quite low pressure difference. Usually pumps can generate much larger pressure difference. If so, the 3/8" should meet the requirement.

In this project, we will use 3/8" tube to build up the outside recirculation system.

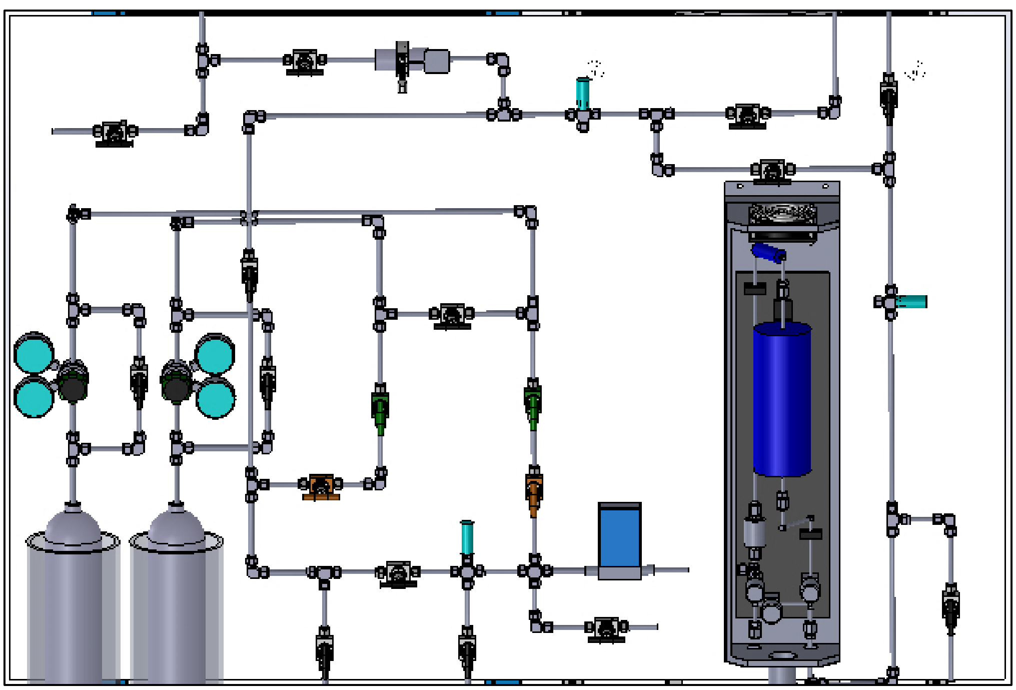

Fig 5.3: 3-D Drawing of Front Panel and Outside Loop

From the above graph, based on the 3-D drawing using SolidWorks, the total length of the tube is roughly:

$$l = 27 + 10 + 55 + 4.7 + 21.5 + 10 + 11 + 49 + 34 + 4.5 + 5.5 + 6 + 41 + 5 + 11.5 + 45 + 9 + 10 + 10 + 11.35 + 34 + 3.3 + 3.3 + 20.5 + 5.2 + 5.2 + 11.4 + 18 + 15 + 7 + 7 + 11 + 30 + 9.7 = 564.7'' \tag{5.37}$$

i.e.

$$l = 564.7'' = 14.34m \tag{5.38}$$

5.2. Dimension of Heat Exchanger

In one journal publication, *Xenon Recirculation-Purification with a Heat Exchanger*, by Columbia Astrophysics Laboratory and High Energy Accelerator Research Organization, a kind of heat exchanger is mentioned and recommended, Model FG3X8-20, by GEA PHE Systems NA, Inc. [4]. Here, in our project, we decide to use the heat exchanger from the same company. But considering the scale of our project is relatively small, we need to choose another type, which is best suited in our system.

Let's first start from studying how temperature changes inside vacuum chamber, heat exchanger, and outside, which is shown in the following graph:

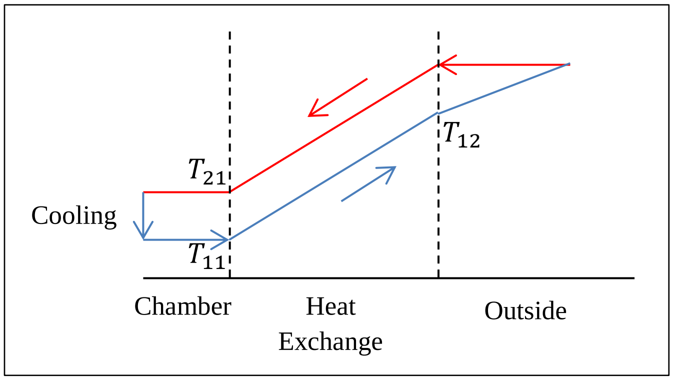

Fig 5.4: Temperature Change along the Recirculation Loop

Initially, the liquid xenon goes from chamber into heat exchanger, where some gas xenon gets into from the outside. In the heat exchanger, heat transfer happens. With some amount of heat transferred into the cold liquid xenon, the cold xenon then becomes gas with temperature going higher, and then comes out of the heat exchanger, and goes into the outside tubes. And then back to the heat exchanger again as high temperature xenon.

We want the flow speed of the gas xenon to be about 20L/min at 1 atm, i.e.

$$q = \frac{20 \times 10^{-3}}{60} = \frac{10^{-3}}{3} m^3/s \tag{5.39}$$

Specific heat

$$c = 158.32 J/(kg \cdot K) \tag{5.40}$$

Evaporation heat

$$\gamma = 12.64 kJ/mol \tag{5.41}$$

For Xe temperature from room temperature (298.15K) to boiling point (165K), cooling power is

$$Q_1 = c\rho q(T_0 - T_b) = 158.32 \times 5.88 \times \frac{10^{-3}}{3} \times (298.15 - 165) = 41.32W \tag{5.42}$$

For condensing Xe,

$$Q_2 = \gamma \frac{\rho q}{M} = 12640 \times \frac{5.88 \times \frac{10^{-3}}{3} \times 10^3}{131.3} 188.69W \tag{5.43}$$

So, totally, the cooling power we need is

$$Q = Q_1 + Q_2 = 41.32 + 188.69 = 230W \tag{5.44}$$

The thermal conductivity coefficient of copper is 401 W/(m.K) at 298 K, 425.8 W/(m.K) at 160K [25],

$$Q = -\lambda A \frac{dT}{dx} = -413.4A \frac{3}{dx} \tag{5.45}$$

Distance between two plates is about 2.24 mm; fluid volume between two channels is 0.03 L, i.e. 30 mL. So the thickness of the copper plate is about

$$dx = 2.21mm - \frac{30000}{86 * 183} = 1.91mm \tag{5.46}$$

So we get the equation,

$$230 = 413.4A\frac{3}{0.00191} \tag{5.47}$$

So

$$A = 354mm^2 \tag{5.48}$$

Consider the situation that we use stainless steel as the material of the plate, the thermal conductivity coefficient at 298 K is 16 W/(m.K) .

By the similar calculation, the area we need is

$$A = 9146.5mm^2 \tag{5.49}$$

The plate area $A_0 = 15738mm^2$ is still enough to meet the requirement, which is the dimension of FG3X8-20.

5.3. Liquid Nitrogen Amount Calculation

In case when the main cooling source, the cryo-refrigerator, stops working, the xenon inside the system will be heated by the outside high temperature environment, and will expand greatly, thus causing the pressure inside the system become very high rapidly, then the system may explode. So a liquid nitrogen loop should be considered to provide the cooling power when emergency happens.

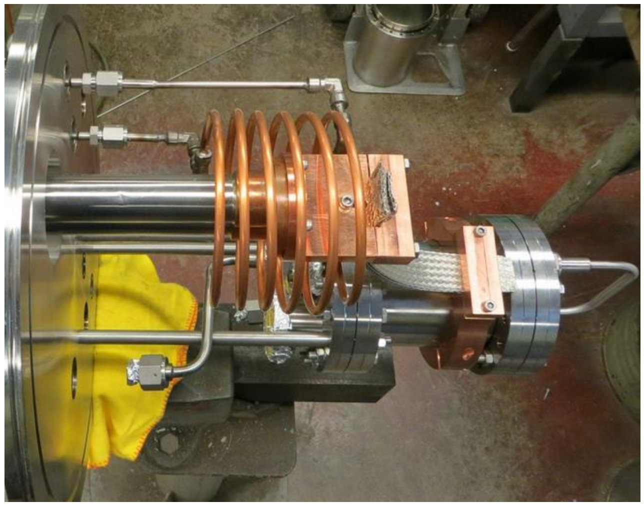

Fig 5.5: Liquid Nitrogen Helical Tube and Flexible Copper Heat Link

Clearly, from the above graph, we need to build up a heat link between the liquid nitrogen tube and a xenon cell, to conduct the heat between them. Considering high performance of copper material in the heat transfer area, and also we need to make the copper flexible to better link the tube and the cell. Then, finally we decide use the copper thermal strap to act as the heat link. Clearly, we need to decide the dimension of the heat link and also need to calculate how much liquid nitrogen per unit time we need to consume in order to make the system run as normal.

5.3.1. Dimension of flexible copper

We know the temperature of liquid nitrogen (77.35 K) and temperature of liquid xenon (161.4~165.02 K), so the temperature difference between LN2 and Xe is

$$\Delta T = 84.05K \sim 87.67K \tag{5.50}$$

The thermal conductivity for copper at 77.35 K is about 580.85 W/(m K), at 160 K is about 425.8 W/(m K), here we estimate by taking the average of the two, which is 503.33 W/(m K) [25].

Suppose the cross area of flexible copper is $15\ mm \times 4\ mm$, then

$$Q = 503.33 \times \frac{0.015 \times 0.004}{l} \times 85.86 \tag{5.51}$$

The power that is used to cool Xe and keep the circulation is about 11.5W (see calculation uploaded to Wiki). To keep the system steady, we need to make the power transferred through the flexible cooper is equivalent to 11.5W.

$$503.33 \times \frac{0.015 \times 0.004}{l} \times 85.86 = 11.5 \tag{5.52}$$

Then, the max length of copper in this cross area dimension is

$$l = 225mm \tag{5.53}$$

The length is enough in our program. Or we can add several pieces of flexible copper, and use the heaters to adjust the temperature we want.

5.3.2. Amount of Liquid Nitrogen

Latent heat of Liquid Nitrogen is 199 kJ/kg, and heat capacity of Liquid Nitrogen is 29.124 J/(mol K), i.e. 1.04k J/(kg K).

For the Nitrogen from liquid to 160 K,

$$q_2 = 1.04 \times (160 - 77.35) = 86kJ/kg \tag{5.54}$$

Totally, the heat capacity of Liquid Nitrogen is

$$q = 199 + 86 = \frac{285kJ}{kg} = 285J/g \tag{5.55}$$

In order to cover the cooling power 11.5W, every second we need

$$\dot{m} = \frac{11.5}{285} g/s = 0.04g/s \tag{5.56}$$

This corresponding to this following volume of unit time

$$\dot{V} = \frac{\dot{m}}{\rho} = \frac{\frac{0.04}{0.808} ml}{s} = 0.05ml/s \tag{5.57}$$

5.4. Dimension of Recovery Bottle

Here, the density of liquid Xe (boiling point & 1 atm) is $3.057 \times 10^3 kg/m^3$, the volume of liquid Xe is about 1~2 liters, then its mass is

$$m_{max} = \rho V = 3.057 \times 2 = 6.114kg \tag{5.58}$$

At 15 ℃ and 1 atm, we can get the density of gas Xe is

$$\rho = 5.584kg/m^3 \tag{5.59}$$

Then the volume of xenon gas at 15 ℃ & 1 atm is

$$V = \frac{m_{max}}{\rho} = \frac{6.114}{5.584} = 1.095m^3 \tag{5.60}$$

At 2500 psi (170 atm) pressure condition:

$$V' = \frac{1.095m^3}{170} = 6.44L \tag{5.61}$$

In the project, we choose to use cylinders from Swagelok, and we ordered two cylinders, 304L-HDF8-1GAL, whose volume is 3.785 L (1 Gallon) for each.

CHAPTER 6: EQUIPMENT TESTING & CALIBRATION

Before we carry on the formal experiments, we need to do several tests and calibrations of the equipment. Here, I describe the tests of thermal sensors (PT 100 and DT 670), and the calibration of the level measurement sensors and controller.

6.1. Testing of Thermal Sensors

The two kinds of thermal sensors are shown below:

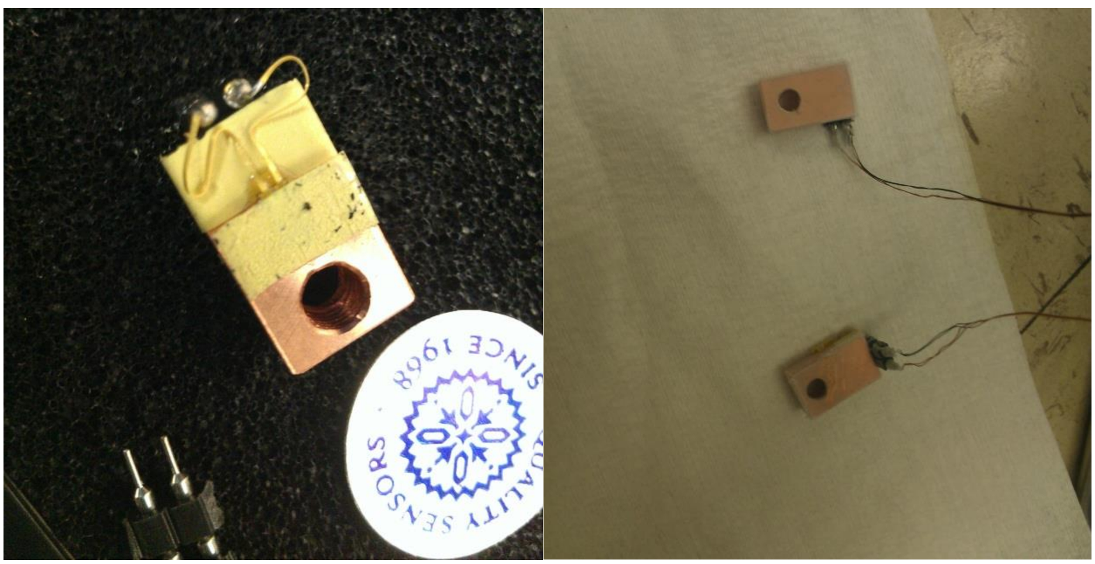

Fig. 6.1: Thermal Sensors DT 670 (left) and PT 100 (right)

Since the two kinds of thermal sensors are calibrated by only a few temperature points when ordered (see Appendix A for more information about thermal sensors), in order to make sure they can give the correct reading, a series of tests are needed. For the tests of thermal sensors, the experimental setup is shown below:

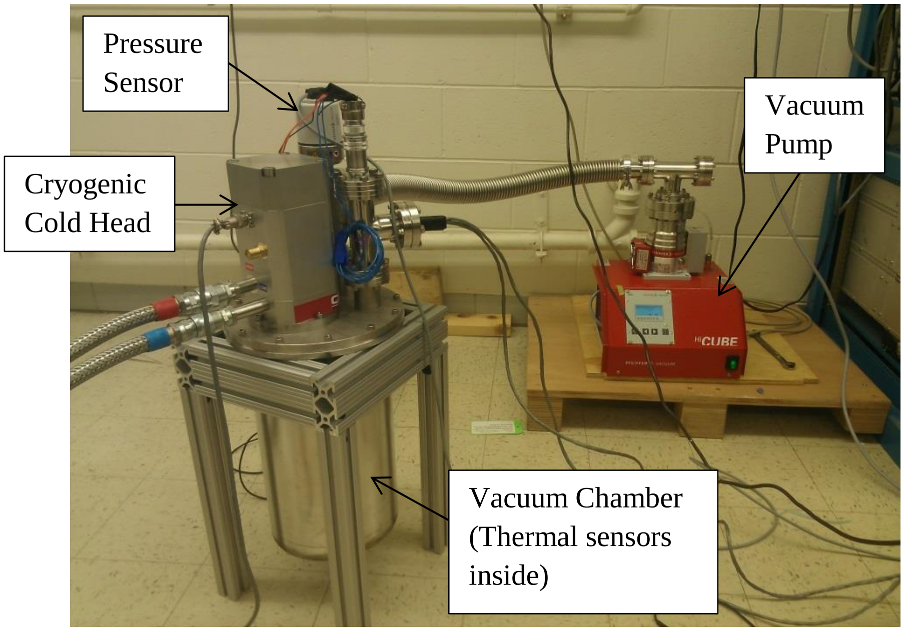

Fig.6.2. Experimental Setup for Thermal Sensor Testing

We use a chamber to build up a vacuum environment for the sensor, to reduce the amount of heat transfer. Inside the vacuum chamber, a super-insulation membrane is used to cover around the cryogenic cold head, to reduce the radiation at very low temperature (30K). The two kinds of sensor are mounted on the cold head inside the chamber, to measure the temperature of the cold head. In addition, we mounted some heaters on the cold head, which are used to adjust the temperature, and to measure the cooling power of the cold head at different temperatures. Also the heaters are used to make temperature stay at a desired value, to calibrate the accuracy of thermal sensors.

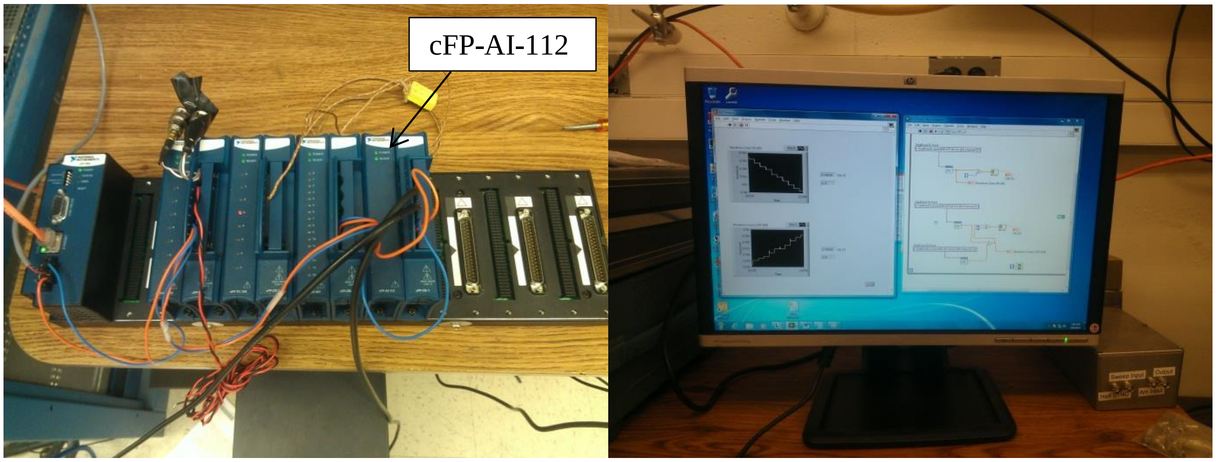

Fig.6.3: FieldPoint and LabView Data Acquisition

The thermal sensors can only give out voltage signal, which is analog signal, so we need the FiledPoint to make the PC able to commnunicate with the sensors. FieldPoint is a programmable automation controller (PAC), and is the product developed by National Instruments Corporation. In the testing of the thermal sensors, we mainly need to use cFP-AI-112 modules, which is an Analog-Input module and covert analog signal into digital signal, which can be accepted by PC.

As stated in Chapter 3, more than one channels will interfere each other, if no differential amplifiers are applied in the circuits. With amplifiers soldered on the circuit board, the four sensors can give as low as 2 K temperature difference. Below is one result:

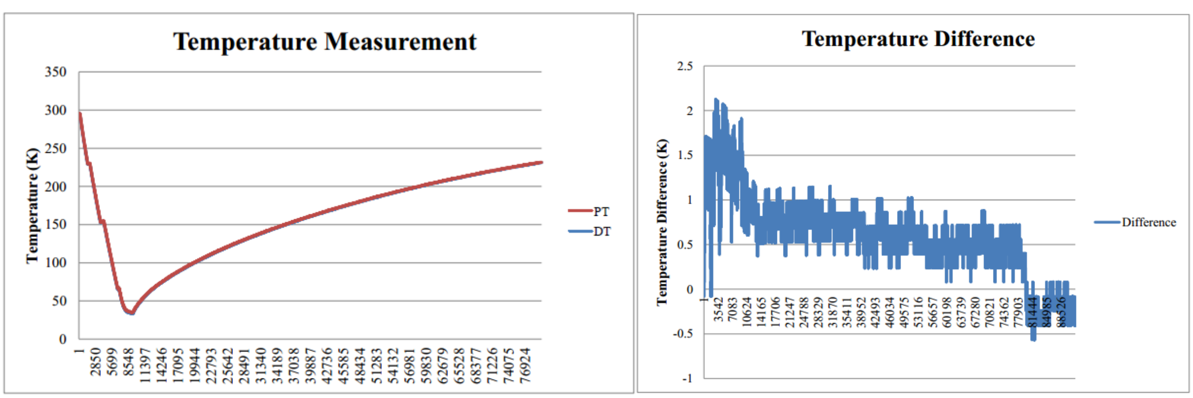

Fig 6.4: Temperature Measurement (left) and Temperature Difference (right) of PT 100 and DT 670

From the results given by the above graphs, the temperature readings given by PT 100 and DT 670 are very close to each other, within 2 K difference.

6.2. Calibration of the Level Measurement Sensors and Controller

In the project, we care about the level of liquid xenon inside the small Xe cell in the large vacuum chamber, and also the level of liquid nitrogen in the dewars of Feed & Bleed Sub-system, which has been described in Chapter 2. The sensors and controller that we are using in the project are as follows:

- Liquid Xenon Level Sensor with 1.33” Conflat Flange

  This sensor is capacitance-based liquid lelvel sensor. It is specially made to meet the characteristics of different liquid, because different kinds of liquid have different dielectric constant, which is related with capacitance. and the 1.33” conflat flange is used to mount the sensor into the cell.

- Standard Liquid Level Sensor for LN_2 Application

  Since the inner depth of the Liquid Nitrogen dewars is 24.0 inches and we don’t need to fill them full with liquid nitrogen to cool the xenon cylinders, we make the active length of level sensors be 20 inches, a bit less than the inner depth of the dewars.

- Model 286 Liquid Level Controller
- Oscillator/Transmitter Kit

  Oscillators are used to connect sensors to the instrument for Input C and D, because Input A and B have internal oscillators installed, only Input C and D need oscillators.

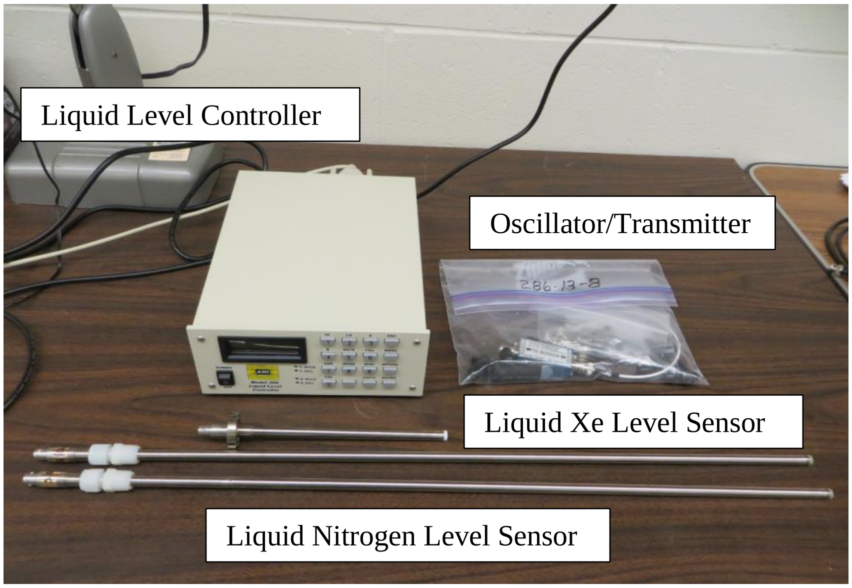

Fig.6.5: Liquid Measurement Sensors and Controller

Below is the calibration process of the level sensors. Since for the Liquid Xenon Level Sensor, the calibration is already done by the company, then we only need to calibrate the Liquid Nitrogen Level Sensors.

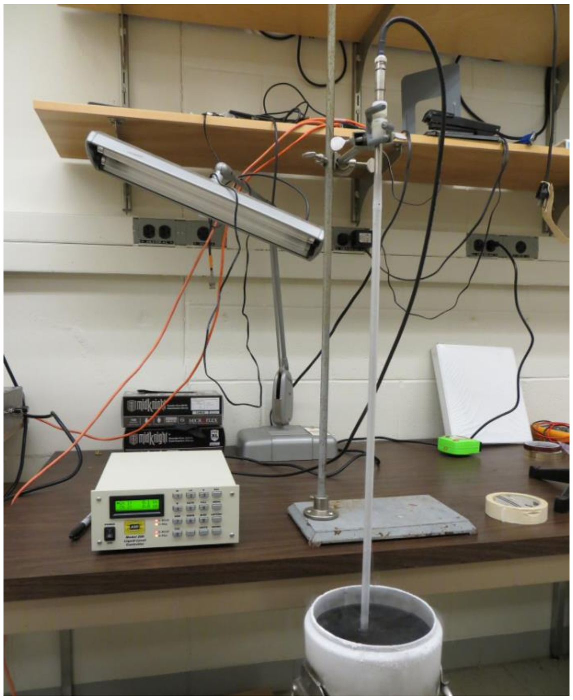

Fig.6.6: Calibration of the Level Measurement Sensors and Controller

Since the Controller 286 can at most work with 4 sensors, and we have 3 sensors in this project (one for liquid xenon and the other two are for liquid nitrogen), the first thing before calibration is assigning each sensor to one channel. Here, without losing generality, we assign CH1 to the liquid xenon level measurement sensor, and CH2 and CH3 to the liquid nitrogen level measurement sensors. The calibration process for each sensor is mainly devided into three steps: calibration for the MIN point and calibration for the MAX point, between which is the active length; and set the total active length.

1) Calibration for MIN point of the sensor

The calibration is shown in the following picture:

Fig. 6.7: Calibration for MIN Point of the Sensor

When we calibrated the MIN point on the sensor, which is the lowest level that the sensor can measure, make the liquid nitrogen level just submerge the bottom hole, and set the lowest point using the controller.

2) Calibration for MAX point of the sensor

The calibration is shown in the following picture:

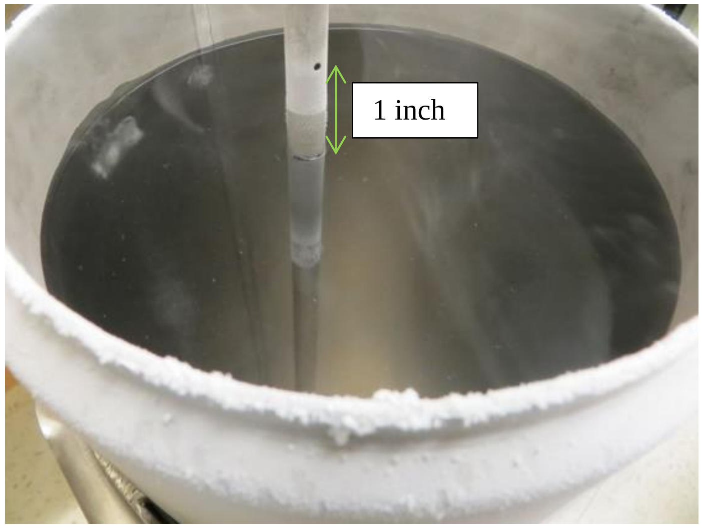

Fig. 6.8: Calibration for MAX Point of the Sensor

Since the active sensing length of the sensor is from the low vent hole to the high point where is 1” below the high vent hole, then the MAX point should be set at the place where is 1” below the high vent hole. Fill in the liquid nitrogen to just submerge that point, and use controller to set the highest measuring point.

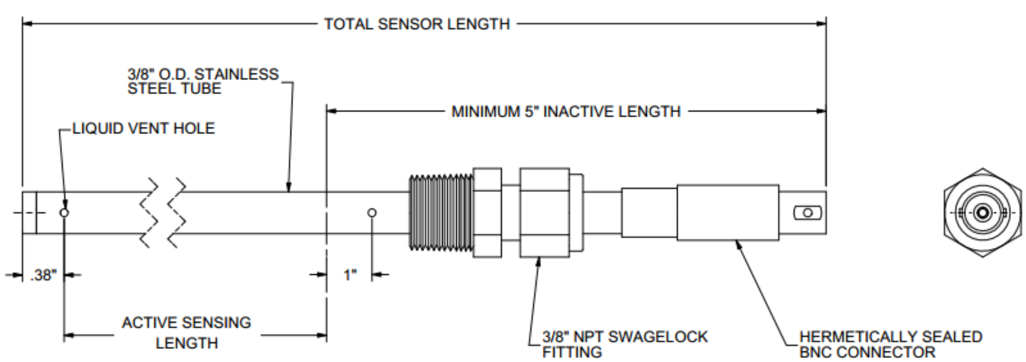

Fig. 6.9: Drawing of Level Measurement Sensor

3) Set the Total Active Length

Input the total active measuring length of the sensor into the controller. For liquid nitrogen sensors, the active sensing length is 20”.

By now, the calibration for the level measurement sensors is done. Then the calibrated sensors can measure the liquid level of liquid nitrogen, with level falls between the MIN and MAX setpoint.

6.3. Test of Pressure Transducers

Another sensor that needs to be tested is pressure transducer. Since we want to know the pressure of the system at different positions, several pressure transducers are mounted at different positions of the out loop. The pressure measured range is 0 to 30 psi (2.04 atm), and the output signal is current, with range 4 to 20 mA. There is a perfect linear relationship between measured pressure and output current.

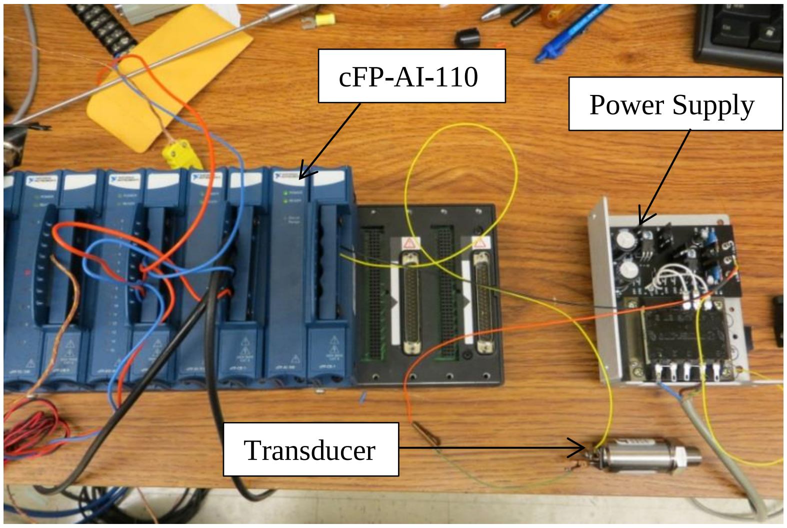

Fig. 6.10: Testing of Pressure Transducer

We use the cFP-AI-110 module to acquire thecurrent signal from the pressure transducers. Additionally, a power supply of 24 V is needed, to drive the transducer. By connecting the transducer into the circuit, and apply different pressure environment to the sensor, we can get corresponding pressure readings.

Since vacuum pump is used in other experiment of EXO project, only the pressure in the lab was measured. The sensor gives the output current of 11.6 mA. Accroding to the linear relationship between pressure and output current, the corresponding pressure is

$$p = \frac{30\ psi}{(20 - 4)\ mA} \cdot (I - 4)\ mA = (1.875 \cdot I - 7.5) psi \tag{6.1}$$

where I is the measured current given by the transducer.

Then,

$$p(I = 11.6) = 1.875 \cdot 11.6 - 7.5 = 14.25\ psi \tag{6.2}$$

The result given by the sensor is about 1 atm (14.7 psi). Since the lab is open to the outdoor, so the pressure in the lab is 1 atm (or very close).

CHAPTER 7: FUTURE WORK

7.1. Construction and Commissioning of Apparatus

All the basic things have been done, and the next step is to assemble all the devices.

7.1.1. Outside Loop

Since the tubes are already in the lab, the next thing is to cut the tubes into different segments, according to the 3-D modeling. The fittings and connectors which are used to build up the loop and connect tubes together also need to be ordered. And the fittings and connectors are as follows: VCR fittings, crosses, tees, male-to-female adapters, female-to-male adapters, and adapter for rupture disc.

Besides, all the manual valves, proportional valves, block valves, pressure regulators, flow meters, pressure transducers, rupture disc, purifier, etc. are needed to be connected into the loop. Then, the entire outside loop will be mounted on the large aluminum panel, which is convinient for users to manage and control the system’s running. Finally, the panel will be supported by two or three lab racks.

7.1.2. System Inside Vacuum Chamber

Thermal sensors will be finally mounted on the cell and on the heat exchanger inside the vaccum chamber. The wires for the PT 100 and DT 670 sensors, and special wires for thermocouples will also be soldered to the sensors. Thermal sensors will be connected through different feedthroughs, to send the signal from the inside chamber to outside, and be processed by computer, or other terminals.

7.2. EXO R&D Tests

7.2.1. Studying Efficiency of the Heat Exchanger

Since the system will be running for a considerable amount of time, efficiency of heat transfer between two phases' xenon becomes an important issue. In the project, we use a cryorefridgerator to provide cooling power to the system, or use liquid nitrogen as an alternative cooling in the case of emergency. For a long-time running experiment, the cooling energy consumed by xenon is quite large.

Heat exchanger is a very useful tool to make use of the heat that is transferred between gas xenon and liquid xenon. Research report by AIR LIQUIDE Advanced Technologies Division and Laboratoire SUBATECH in France, and High Energy Accelerator Research Organization in Japan, states that using a heat exchanger is a good way to recuperate more than 95% of heat for evaporating liquid xenon to recondense the purified xenon. Our system will be used to test the efficiency using a heat exchanger. The results will be useful for future tonne scale xenon experiment.

7.2.2. Testing Cold Readout Electronics

Since in the future large scale xenon experiments, great many electronic signals will be measured and recorded, which will be used for analysis [10, 15]. This small scale system will be used to test the electronical signal in the future experience. Electric field will be built up in the xenon cell using electrodes, to collect the electrons that excited by particle depositing energy. Also, avalanche photodiodes (APDs) will be built up, to collect scintillation. Additionally, some other electronics equipment will be installed inside the system, to measure signals that may be needed in large scale xenon experiment.

7.2.3. Building up Small TPC

Time Projection Chamber (or TPC) is a particle detector used in particle collisions or other high energy experiment, and is used to record detailed tracks of charged particles, with particle detectors [9, 17]. TPC can allow physicists to analyze particle collisions in three dimensions. To measure the momentum of charged particles, electric and magnetic fields are needed to built up in the chamber, and the two fields need to be parallel to each other, to minimize the diffusion of the electrons coming from the ionization.

In the future experiments with the small scale setup, electrodes will be built up to generate electrical field, and other devices will be needed to generate magnetic field. Some other detectors and devices, like CCD Camera and photomultiplier, may also be assembled in the system for signal detection and other purpose.

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APPENDIX A: LIST OF EQUIPMENT IN THE PROJECT

Table A.1: List of Equipment in the Project

Item	Company	Part Number	Quantity	Brief Description
Gas System				
Manual Valve [Xe] 3/8" / 1/2"	Swagelok	SS-6BG-V19 SS-8BG-V47 SS-8BG-VCR SS-6BG-BW6 SS-8BG-BW8 SS-6BG-TW SS-8BG-TW	15	- Butt welded female VCR - Butt welded female VCR - integral male VCR - Tube butt weld, - Tube Butt weld, - Tube socket weld and Tube Butt weld - Tube socket weld and Tube Butt weld All: gasket seal, all SS, 1/2", up to 1000 PSIG
Proportional Valve [Xe]	MKS	248A-10000-RV	2	Needs valve driver 1249A
Control Valve Driver	MKS	1249A	2	For the 248A
Block Valve [Xe]	MKS	CVNL-4F-ECNCV-24DC	2	Standard Configuration
Block valve [Xe baloon]	N/A	N/A	2	Used ones at NPL
Xe Recovery Baloon	Flexi Liner	N/A	1	Calculated for 2 ltr of LXe, M ~ 6 kg, V(Baloon) ~ 1040 ltr (minimum at Std. cond.) Offers will be sent for vinyl based polymer, thickness 0.065" and 0.05"
Flow Meter	MKS	GM50A006204TB3010	1	
Pressure Transducer	Omega	PX319-030AI	3	
Rupture disc [Xe]				VCR - rupture disks
Purifier [Xe]	SAES Pure Gas, Inc.	PS4-MT3-R-1	1	
Recirculation pump [Xe]	KNF	PM26866-143.12	1	
Cryorefrigerator	Cryomech	PT60	1	
Heat Exchanger	GEA	FG3X8-14	1	

Table A.1 (cont.)

Item	Company	Part Number	Quantity	Brief Description
Feed/Bleed bottles [Xe]	Swagelok	304L-HDF8-1GAL	2	1/2" Female NPT connection
N2 dewars for Feed/Bleed bottles	Cryofab	CF624	2	
Regulators Feed/Bleed bottles [Xe]	Mc Master	66325A41	2	5-125 PSI (0.3 - 8.5 atm) operating pressure 0 - 4000 PSI gauge, check for NPT male & VCR connection
LN2 Supply Dewar	N/A	N/A	1	Borrow from Another Lab
Tubing , Ltot ~ 50ft	Mc Master	3334K22	9	Ultra-High-Polish Type 316/316L, meets ASTM A269 and A27, Electropolished+Cleaned with DI water, 9x6 ft = 54 ft total length
Fittings/adapters	Swagelok			
Vacuum pump	Pfeiffer	PM S03 556 A	1	
Kapton Heater	Omega	KHLV-202/(*)-P (*) = (10)	1	28 V, 40 W/inch2, A = (2x2)" = 25 cm2, Power: 160 W, Rated up to 200C, Imax = 5.7 A
Panel	Mc Master	88835K211	1-2	size: ~(6x6) ft, ~1/4" , Alumina best fitting: 48"x72" = (4x6) ft = (1.8x1.2) m, d = 0.2" = 5.1 mm
Temperature Measurement				
Thermocouple, T-type	Omega	5TC-TT-T-20 -36	1	5 TC's package, 20AWG=0.8mm
Duplex TC wire, T-type Constantan/Copper	Omega	TT-T-20-SLE-100	1	PFA, Special limits of error, 100 ft, AWG 20
TC feedthrough, 5 pairs	Lesker	TFT5TN00003	1	CF 2.75 with Loop Connectors
El. feedthrough [other]	CeramTec	18897-01-CF	1	CF 2 3/4, 19 Pins, with connector , 1kV DC, 5 A /pin

Table A.1 (cont.)

Item	Company	Part Number	Quantity	Brief Description
Liquid Nitrogen Level Measurement				
Liquid Level Controller	American Magnetics	286 CE	1	2x LN sensors + 1x calibrated LXe sensor + Custom Sen Kit (Oscillator/Transmitter Kit)
Cryo valves (LN2)	ASCO	8263H125LT	3	24 VDC, 0.5 A

APPENDIX B: CONTROL SIGNAL AND CONTROL MODULE

Table B.1: Control Signals

Item	Quantity	Control Signal (Input)	Output Signal	FieldPoint Module
Block Valve [LN_2]	3	24 DC (Current 0.48 A)	/	cFP-DO-401
Block Valve [Xe]	2	24 DC (Current: 1.3 A (initial) 0.3 A (running))	/	cFP-DO-401
Flow Meter	1	/	0-5 VDC, or 4-20 mA	cFP-AI-112, or cFP-AI-100
Liquid Level Controller	1	/	0-10 VDC, or 4-20 mA	cFP-AI-112, or cFP-AI-100
Pressure transducer	3	/	4-20 mA	cFP-AI-100
Proportional Valve [Xe] (with Driver 1249A)	2	0-5 VDC, 0-10 VDC, or 4-20 mA	/	cFP-AO-210
Thermocouple	5	/	Voltage	cFP-TC-120
Variable Frequency Driver (with Recirculation pump [Xe])	1	0-10 VDC	/	cFP-AO-210

Table B.2: Control Modules

Module	Details	Number of Channels
cFP-AO-210	0 to 10 V outputs (up to 10 mA per channel)	8
cFP-TC-120	Thermocouple (standard J, K, T, N, R, S, E, and B types)	8
cFP-DO-401	16 sourcing digital outputs, Output range: 10 to 30 VDC, sourcing; Up to 2 A per channel, 8 A squared per module	16
cFP-AI-112	60 mV to 10 V inputs	16
cFP-AI-110	Voltage (-10 V - 10 V) or current (-20 mA - 20 mA) inputs	8